Met Office

Application of bias correction to the Met Office operational storm surge forecast

Forecasting Research Technical Report No. 666

January 2025

Clare O'Neill, Andy Saulter, Christopher Stokes, Breogán Gómez

https://doi.org/10.62998/tymo5223

© Crown Copyright 2025, Met Office

Met Office

Document history

Version	Purpose	Date
0.1	Draft	22 November 2024
0.2	Revisions	16 December 2024
1.0	Final version	13 January 2025

Prepared by

Clare O'Neill, Senior Scientist – Surge Modelling, 22 November 2024

Reviewed by

Christopher Stokes, Science Manager – Surge and Waves Monitoring and Prediction, 2 December 2024

Andy Saulter, Head – Ocean Forecasting Research and Development, 2 December 2024

Authorised for issue by

Christopher Stokes, Science Manager – Surge and Waves Monitoring and Prediction, 13 January 2025

© Crown Copyright 2025, Met Office

Met Office

Contents

Document history 1

Summary 3

1 Background 4

1.1 Storm surge forecast system 4

1.2 Hindcast 5

1.3 Observations 5

2 Bias correction methods 6

2.1 Mean Sea Level correction 6

2.2 Seasonal correction 6

2.3 Grid-wide constant offset 8

2.4 Site-based MSL offset 9

2.5 Site-based harmonic analysis of errors 9

3 Results 10

3.1 Case study examples 10

3.2 Overall statistics 14

4 Conclusion and operational implementation 35

5 Use of the surge hindcast 39

References 40

Appendix A Statistics timeseries for all class A sites 41

© Crown Copyright 2025, Met Office

Summary

The Met Office runs an operational storm surge forecast system for the UK based on a 7 km configuration of NEMO forced by wind and air pressure from Met Office global atmosphere forecasts. The water level forecast comprises the surge residual from the model added to the harmonic tide prediction derived from observations.

A new automated bias correction has been added to the system to improve forecast performance. The correction has 3 components: a mean sea level correction to account for different mean sea levels in the forced and unforced model runs, a monthly correction to account for the atmospheric component included in harmonic tide predictions, and an empirical constant correction to account for sea level rise and other effects not currently included in the surge model.

The correction scheme is shown to significantly improve the overall forecast skill compared to the original uncorrected forecast. The number of forecasts that fall outside the target 20 cm accuracy is reduced from an average of 17% (whole tide cycle) and 22% (high waters only) to less than 6% (in both cases). The average RMS error is reduced from 14 cm (whole tide cycle) and 15 cm (high waters) to 9 cm (in both cases) and the average bias is reduced from 11 cm to 1cm (all tide cycle) and 13 cm to 3 cm (high waters).

The correction was added to the operational system in August 2024.

© Crown Copyright 2025, Met Office

1 Background

1.1 Storm surge forecast system

The Met Office runs an operational forecast system for storm surge in the UK. The system comprises an ocean model based on a 2D configuration of NEMO which is forced with wind and air pressure forecasts from Met Office global atmosphere forecasts. The surge model has horizontal resolution of approximately 7 km and the wind/pressure forcing 10-20 km. This configuration isn't designed for coastal forecasting as this resolution is too coarse, but rather the model is used to provide an estimate of the water level adjustment that is needed to improve the background harmonic tide prediction.

The model runs 4 times a day in both deterministic and ensemble modes producing a forecast for up to 7 days. A tide-only configuration (with no wind or air pressure forcing) is also run and the difference between the two runs is the model surge residual forecast, representing the contribution to total water level induced by atmospheric surge. Calculating the surge using these two runs rather than simply running the model with no tide forcing ensures that the non-linear effects of the tide-surge interaction are included within the model surge residual.

To produce the forecast of total still water level, the model surge residual is added to the predicted tide from harmonic analysis of long-term observations, provided by the National Oceanography Centre (NOC). Thus the predicted total water level has a robust vertical datum that originates from the tide gauge data at that location. Further details on the surge model and operational system are given by O'Neill et al. (2016), O'Neill and Saulter (2017).

The target accuracy of the system is for the total water level forecast to be within 20 cm of the observed level. There is potential for both the harmonic tide and model surge components that make up the total water level forecast to have systematic errors (bias) and more random errors. The aim of this work is to minimise the systematic errors.

Systematic biases are known to exist in the storm surge predictions for reasons including:

- Vertical datum discrepancies between the observation and tide prediction
- Discrepancies between the model vertical reference zero level and the tide prediction
- Changes in mean sea level since tide calibration (the surge model is not designed to predict this)
- Double counting of radiational tide effects (see section 2.2)

Although no automated bias correction has been performed up to now, guidance has been issued to forecasters in the form of a spreadsheet containing monthly suggested corrections at Class A tide gauge locations (Figure 1). Two versions were provided - a correction for high tide times, and a correction for the rest of the tidal cycle. These were created by comparing model predictions with observations over the previous year and calculating monthly average differences, with the calculations updated every summer.

© Crown Copyright 2025, Met Office

The bias correction methods outlined in this report are intended to reduce or remove this need for manual forecaster intervention by automatically including corrections in the forecast products. This also has the benefit of being able to correct other locations not covered by the spreadsheet (due to lack of observation data).

1.2 Hindcast

The Met Office have recently completed a 40+ year hindcast (1979–2022) using the same model setup as the operational surge forecast, but with atmospheric forcing (10m winds and mean sea level pressure) from the ERA5 global reanalysis (Hersbach et al., 2020) instead of Met Office operational forecasts. This hindcast dataset has provided the opportunity to address some of the long-standing biases present in the surge forecast system which require a long timeseries of data to resolve.

1.3 Observations

The surge predictions are routinely verified against tide gauge observations from the UK Class A tide gauge network which comprises the locations shown in Figure 1.

Figure 1: Class A tide gauge locations

Observations of water level are recorded at 15-minute time resolution. Processed quality controlled data are available from BODC, however this dataset is intended to be suitable for long-term sea level analysis

© Crown Copyright 2025, Met Office

which means that large amounts of data are rejected during the quality control process. This makes it less appropriate here where we are interested in individual surge events. Therefore for this work we use a separate quality controlled dataset updated monthly by NOC which is specifically focussed on storm surge applications (NOC, personal communication). This dataset is available from October 2019 but for this work use the most recent 2 year period (August 2022–July 2024) as this is more representative of present sea level conditions.

2 Bias correction methods

Five bias corrections are trialled and are applied cumulatively, ie option 2 is applied in addition to option 1, and option 3 is applied in addition to 1 and 2 etc. The first three methods are applied to the entire model grid so may be used to correct any desired location. The final two corrections are site-based and require a long recent timeseries of available good quality observed data at the location, so would likely only be possible for the class A tide gauge locations in the operational system.

2.1 Mean Sea Level correction

The NEMO ocean model is not explicitly referenced to an external vertical reference frame but the model zero level in the absence of any forcing can be taken as equivalent to the geoid (a theoretical surface that approximates global mean sea level under Earth's gravity alone). The model mean sea level is then the average effect of all of the forcings applied to the model, which will be different between the tide-only and tide plus meteorology runs. Therefore when the tide-only run is subtracted to calculate the model residual there is a small discrepancy from the water levels in the two runs not having the same reference.

The mean sea level correction is calculated by taking the mean from the hindcast across the full 40 years. This field is then subtracted from the surge forecast.

Figure 2 shows the MSL correction around the UK. There is a general north-south gradient reflecting average air pressure and wind patterns.

2.2 Seasonal correction

The tide predictions used as part of the water level forecast system are calculated from harmonic analysis of a long time-series of observations from tide gauges. This process assumes that the resulting harmonics, including the long period constituents, are entirely astronomical in origin. These include *Sa* (Solar annual) and *Ssa* (Solar semi-annual) which in reality are dominated by non-tidal effects (radiational effects, Williams et al. (2018a)) including seasonal variations in storminess, solar heating and

© Crown Copyright 2025, Met Office

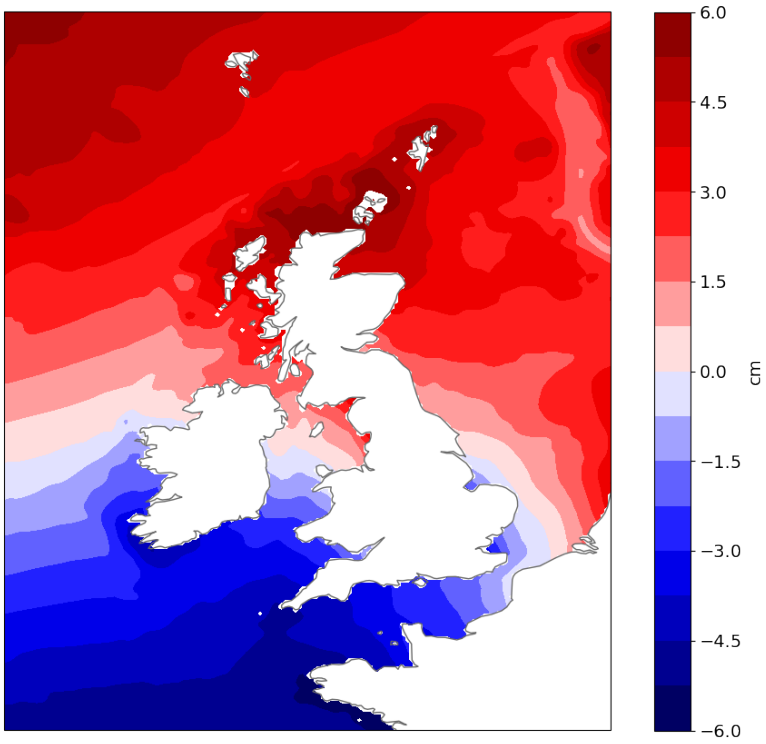

Figure 2: Mean Sea Level correction. Values are subtracted from the forecast

river run-off. Therefore the harmonic tide prediction includes a 'radiational tide' contribution derived from average meteorological conditions, which may or may not be a good fit for the present year.

The model tide-only run in contrast does not include any tide constituents with period longer than around 1 day, so seasonal variations are not present in the model tide. The surge residual is calculated by subtracting this model tide from the full model run, so in the model seasonal atmospheric effects are entirely included within the surge residual. Note that since the present model is barotropic the only effects included are variations in wind and pressure, with other effects such as steric changes from heat and fresh water fluxes excluded.

Within the operational system the model surge residual is added to the harmonic tide prediction, meaning that there is an element of 'double counting' as the resulting water level forecast includes both a seasonal variation based on average weather conditions (included in the harmonic tide) plus the seasonal variation due to actual storminess in the current time (included in the modelled surge residual). Similarly when comparing the surge residual rather than total water level, the harmonic tide is removed from the observed water level to calculate the 'observed surge residual' resulting in this seasonal component of surge being removed from the observation. Average seasonal weather effects are therefore removed from the observed residual and assigned to the tidal component of the observed water level. The result is that the modelled and observed surge residuals are not directly comparable with one another in the present system. This effect is described in more detail by Williams et al. (2018a), Williams et al. (2018b) and Flather et al. (2000).

© Crown Copyright 2025, Met Office

The impact on the surge forecast can be seen most clearly at the locations in the north of the UK where there is a strong seasonal signal in forecast bias when compared with observations. Figure 3 shows an example for Kinlochbervie (north Scotland).

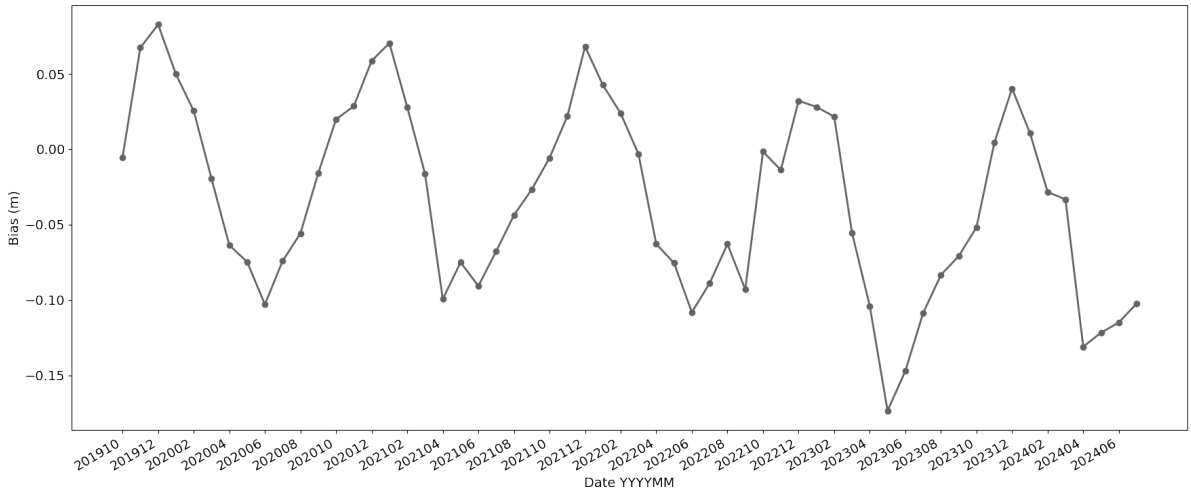

Figure 3: Model surge residual bias compared to observations at Kinlochbervie

To counteract this seasonally varying bias, the mean model water level is calculated for each month over the 40 year hindcast period. The resulting monthly climatology is used to correct the model forecast by linearly interpolating the monthly values to the forecast times, and then subtracting the resulting values from the forecast residual. This has the effect of reducing the seasonal variability in model-observation differences.

2.3 Grid-wide constant offset

This correction is an empirical value intended to address effects of sea level rise relative to the harmonic tide prediction mean sea level which are not currently included in the model, for example due to steric heating effects.

The correction is calculated by applying methods 1 and 2 as above, then comparing the resulting water level prediction to the tide gauge observations and calculating the remaining difference. An average is taken over all the locations and applied across the grid. As it is a single value applied at all locations it will necessarily be better for some sites than others but this approach is taken in order to be able to correct for all locations not only the tide gauge locations.

When the initial scoping work for this project was done, using observations over October 2019–January 2024, the average was 7.7cm. From the latter half of 2023 and into 2024 the observed water level across many sites has shown a significant increase compared against the earlier period. Figure 4 shows an example using all sites on the south coast. The analysis has been re-calculated using the new observations and focussing on a more recent period in order to be more representative of current

© Crown Copyright 2025, Met Office

conditions: August 2023–July 2024. As a result, the grid-wide correction has been increased to 10cm. This is the value implemented in the current system, but it will be reassessed annually using up to date observations and adjusted accordingly.

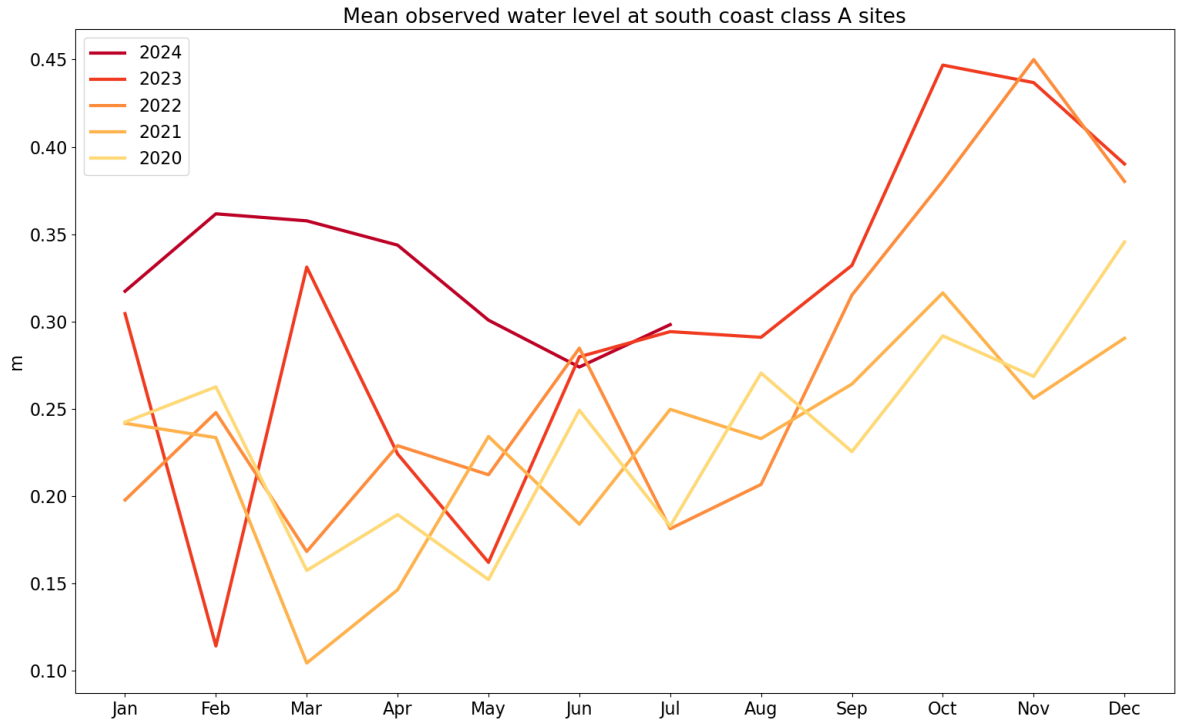

Figure 4: Mean observed water level in years 2020–2024 averaged across the south coast gauges (St Mary's, Newlyn, Plymouth, Weymouth, Bournemouth, Portsmouth, Newhaven, Dover)

2.4 Site-based MSL offset

This is a site-based correction to reconcile the observed and predicted mean sea level, which can be applied where a good quality recent dataset of validation information is available. While the previous methods in Sections 2.1–2.3 above are applied to the gridded model data products, site-based corrections to the forecast data are applied at tide gauge locations only, and override corrections 1 and 3 at the point location.

The mean sea level is calculated over a training period of one year for both the model water level and the tide gauge observations. The difference between these observed and predicted means is calculated and then applied as a local MSL correction.

2.5 Site-based harmonic analysis of errors

For this final option the difference between the predicted (model residual + harmonic tide) and observed water level, after applying the previous bias corrections, is calculated for a year long training period

© Crown Copyright 2025, Met Office

prior to the current year. Harmonic anaylsis is performed on this error timeseries, resulting in a series of constituents which can then be used to reconstruct the expected error for other times. This approach seeks to remove any remaining cyclical biases in the forecast data, that result from the model residual + harmonic tide method. This predicted error is then subtracted from the model forecast.

As the harmonic analysis method requires a long timeseries to produce valid results, this correction can only be performed for sites where there is a good time coverage of high quality tide gauge observations.

Unlike the previous corrections which shift the model prediction up or down but do not change its shape or overall behaviour, this method provides a correction which varies across the tidal cycle[1].

3 Results

The model forecast is compared against tide gauge observations for the uncorrected forecast, after applying the spreadsheet of corrections, and after applying the proposed automated bias corrections (Sections 2.1–2.5) in a cumulative order. The comparisons are summarised in Table 1.

Table 1: The model experiments evaluated in this report. The last 4 experiments were cumulatively added (indicated by '+') to the Model MSL experiment

Experiment name	**Description**
Uncorrected	Uncorrected forecast (current operational product)
UKCFF spreadsheet	Applying the suggested forecaster adjustment spreadsheet
Model MSL	MSL correction from the hindcast
+Seasonal	Seasonal correction, plus model MSL correction
+Gridwide constant	Gridwide constant correction, plus seasonal and MSL
+MSL Reduced to obs	Site-based MSL correction derived from long observations, plus seasonal
+Error Harm correction	Harmonic error correction, plus site-based MSL, plus seasonal

3.1 Case study examples

Figure 5 shows an event at Sheerness in November 2022. This is a common surge pattern here with an initial negative surge phase as winds are blowing offshore before the wind direction shifts and the positive surge begins. The model typically does not represent this transition well, with the negative phase too strong and a lagged build up of positive surge thereafter, which often doesn't catch up with the full magnitude of the positive surge phase. Applying bias corrections 1–4 shifts the model forecast up which leads to some improvement but by design they do not change the fundamental model behaviour. The final correction from harmonic analysis of the errors is generally better than the others, but again does not significantly alter the shape of the prediction as this model error is event based and not predictably periodic.

[1] The seasonal correction described in §2.2 is also time varying, but on a slower monthly timescale that is not significant when looking at the forecast for an individual tide or surge event

© Crown Copyright 2025, Met Office

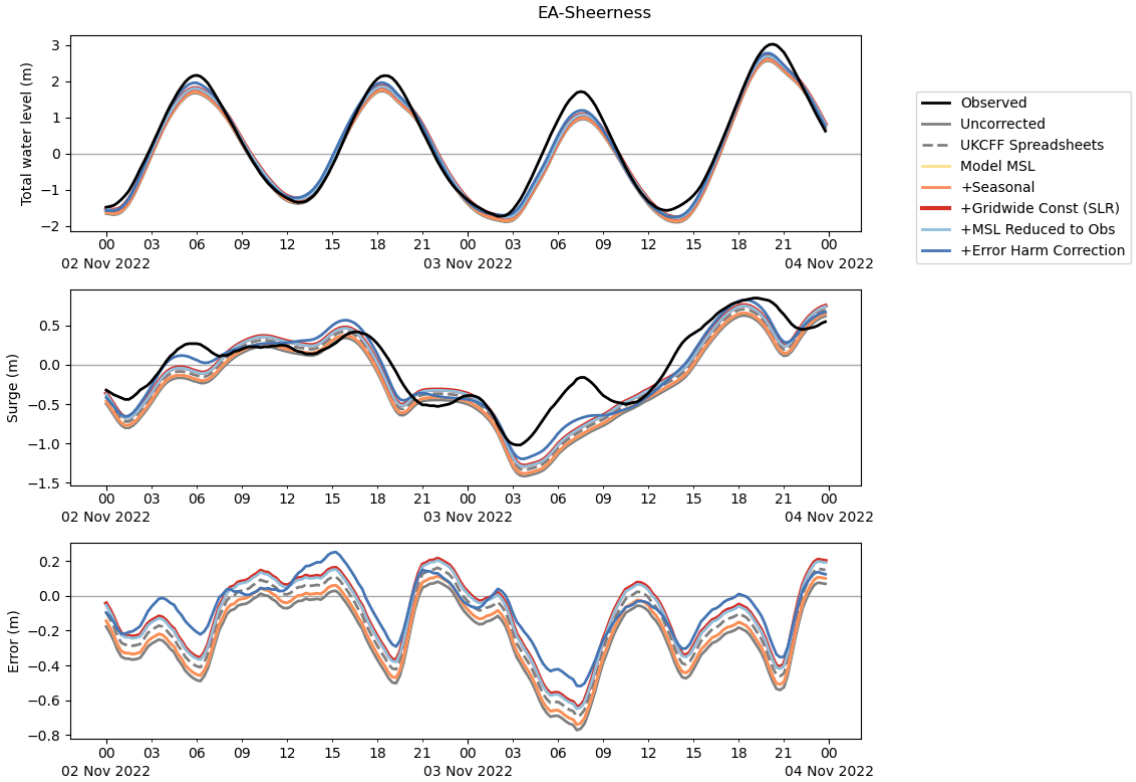

Figure 5: Modelled and observed surge at Sheerness in November 2022 for each experiment. The top panel shows total water level as used operationally (ie model residual + harmonic tide prediction). The middle panel shows surge residual. The bottom panel shows model-observation error

© Crown Copyright 2025, Met Office

Figure 6 shows an example from Newport, a challenging location to forecast due to the complex tides in the Bristol Channel which are known to be incompletely represented in both the model and harmonic tide predictions. The observed surge residual (ie calculated by removing the harmonic tide prediction from the tide gauge observation) here is dominated by large spikes at low tide due to the shape of the tidal curve at this location not being well represented by a harmonic series. As would be expected the model surge does not reproduce this signal since it is independent of the harmonic tide prediction, leading to large model-observation errors. The final bias correction experiment, applying a correction based on harmonic analysis of this error, is able to partially capture the signal. This is not enough to remove the largest errors over the whole tidal cycle but the errors at high water are generally reduced.

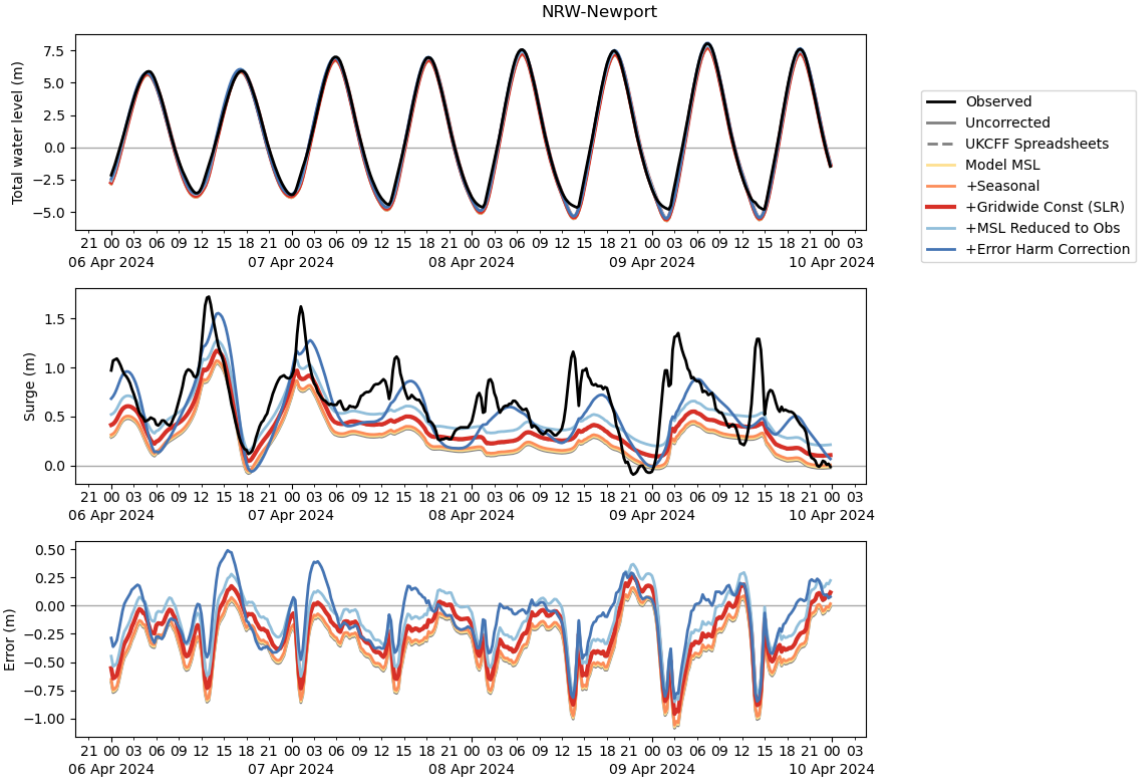

Figure 6: Modelled and observed surge at Newport in April 2024 for each experiment. The top panel shows total water level as used operationally (ie model residual + harmonic tide prediction). The middle panel shows surge residual. The bottom panel shows model-observation error

Figure 7 shows an example from Heysham for a west coast surge event in November 2022. The model generally underpredicts the observed surge and misses the second smaller surge observed at evening high tide on 3 November. The first two corrections initially move the model further away, but then the addition of the gridwide sea level rise component (thick red line) brings the model closer to the observations. The site-based MSL correction is very similar. The addition of the error harmonic correction alters the shape of the model timeseries leading to further improvement, in particular partly capturing the second rise in the residual which was not present before.

Finally Figure 8 shows an example for Aberdeen. In this case the shape of the surge is well forecast by the model, but it is consistently offset and too low. The MSL and seasonal corrections together make

© Crown Copyright 2025, Met Office

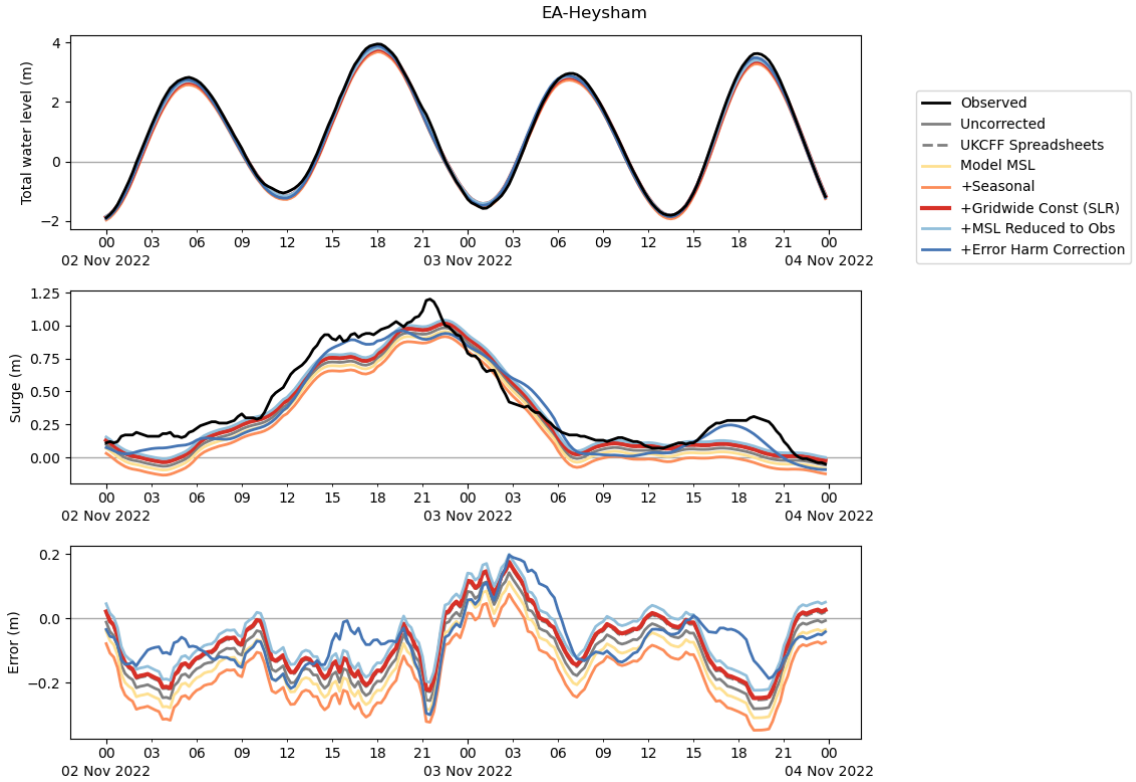

Figure 7: Modelled and observed surge at Heysham in November 2022 for each experiment. The top panel shows total water level as used operationally (ie model residual + harmonic tide prediction). The middle panel shows surge residual. The bottom panel shows model-observation error

© Crown Copyright 2025, Met Office

very little difference during this event, but then applying the gridwide correction brings the model significantly closer to the observed level. It is still generally below the observation but now consistently within the target accuracy of 20 cm. The site-based harmonic error correction makes a further incremental improvement.

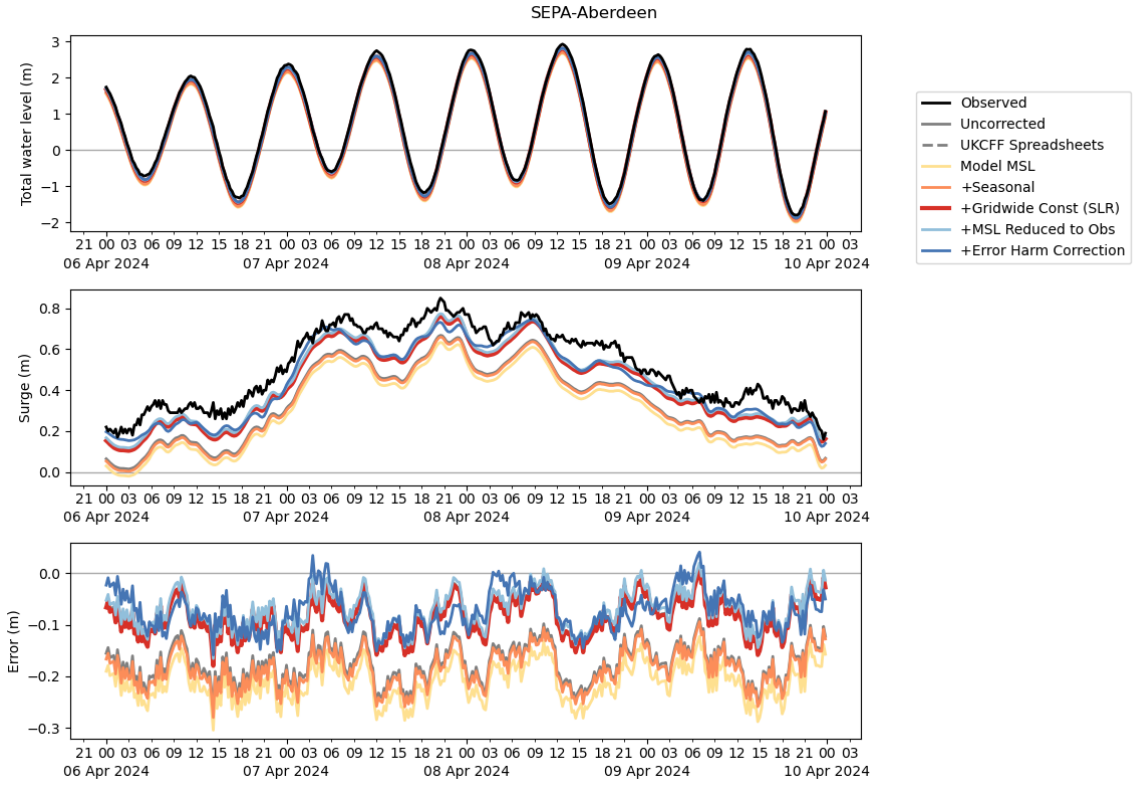

Figure 8: Modelled and observed surge at Aberdeen in April 2024 for each experiment. The top panel shows total water level as used operationally (ie model residual + harmonic tide prediction). The middle panel shows surge residual. The bottom panel shows model-observation error

3.2 Overall statistics

The effectiveness of the proposed bias corrections is quantitatively assessed against the quality controlled observation dataset described in section 1.3. This is done for two timeseries types: the entire timeseries of 15 minute predictions over the 2-year analysis period, giving a measure of the overall performance across the whole tidal cycle; and the skew surge. Skew surge is the difference between peak water level (predicted or observed) and the expected high from the harmonic tide alone, and gives a measure of the skill at forecasting high water levels without being impacted by differences in timing.

In each case the metrics calculated are:

- RMS error [*overall error*]
- Bias [*systematic error*]

© Crown Copyright 2025, Met Office

- Standard deviation of error [*a measure of the consistency of the model error*]
- % of times that the model-observation error is greater than 20 cm. Hereafter referred to as “X200” [*proportion of forecasts outside the target accuracy*]

Figure 9 shows an example for Kinlochbervie, one of the sites with a strong seasonal cycle in the bias. The grey line with the original uncorrected forecast shows this signal in the bias. Applying the MSL correction shifts the bias down but does not alter the seasonal pattern. Adding the seasonal correction (orange line) flattens the bias such that it is much more similar across the 2 year period. Then applying the 10 cm constant correction brings the bias closer to zero, resulting in a significantly improved bias and RMS error compared with the original forecast. The two site-based corrections, shown in the light and dark blue lines, provide a very similiar outcome.

At this location the percentage of forecasts falling outside the target 20 cm accuracy is negligible already for most months in the uncorrected forecast, so this metric is not improved with bias correction (and is initially degraded by corrections 1 and 2 before adding the 10 cm gridwide correction).

The skew surge statistics (Figure 10) show the same behaviour.

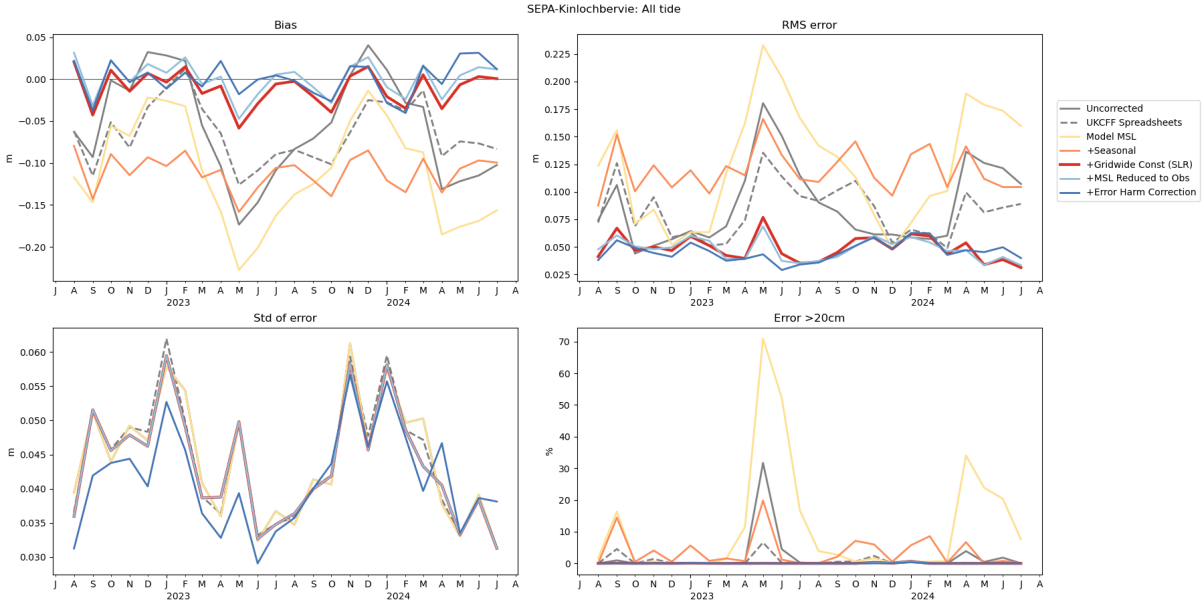

Figure 9: Monthly all-tide statistics at Kinlochbervie for each correction experiment, from August 2022–July 2024

More sensitivity in the X200 statistic is seen at Sheerness, a complex estuarine location which is challenging to forecast. Figures 11 and 12 show that the number of uncorrected forecasts falling outside the target 20 cm range is large, particularly at high water as indicated in the skew surge statistics. This is significantly improved after applying the corrections. In this case there is not much seasonal pattern to the errors so the seasonal correction does not produce additional benefit on top of the MSL correction. The site-based harmonic error correction improves the performance even more.

The standard deviation of errors is also relatively high here compared with other locations, indicating a higher contribution from non-systematic errors. This is significantly reduced by the site-based harmonic

© Crown Copyright 2025, Met Office

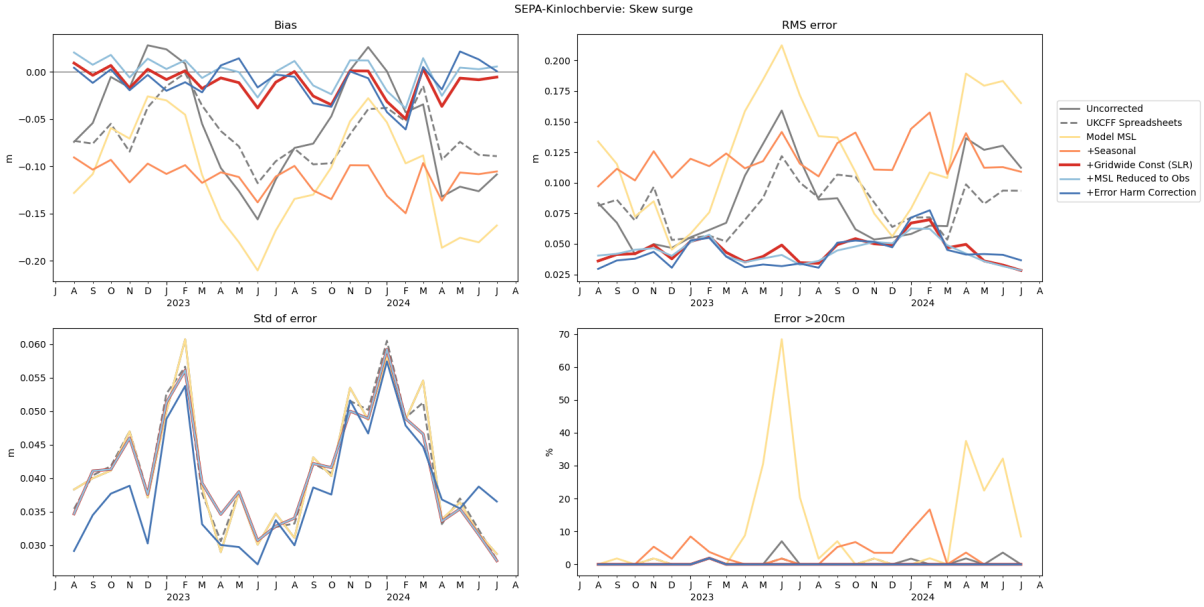

Figure 10: Monthly skew surge statistics at Kinlochbervie for each correction experiment, from August 2022–July 2024

error correction for the all-tide statistics, but not when looking at the skew surge.

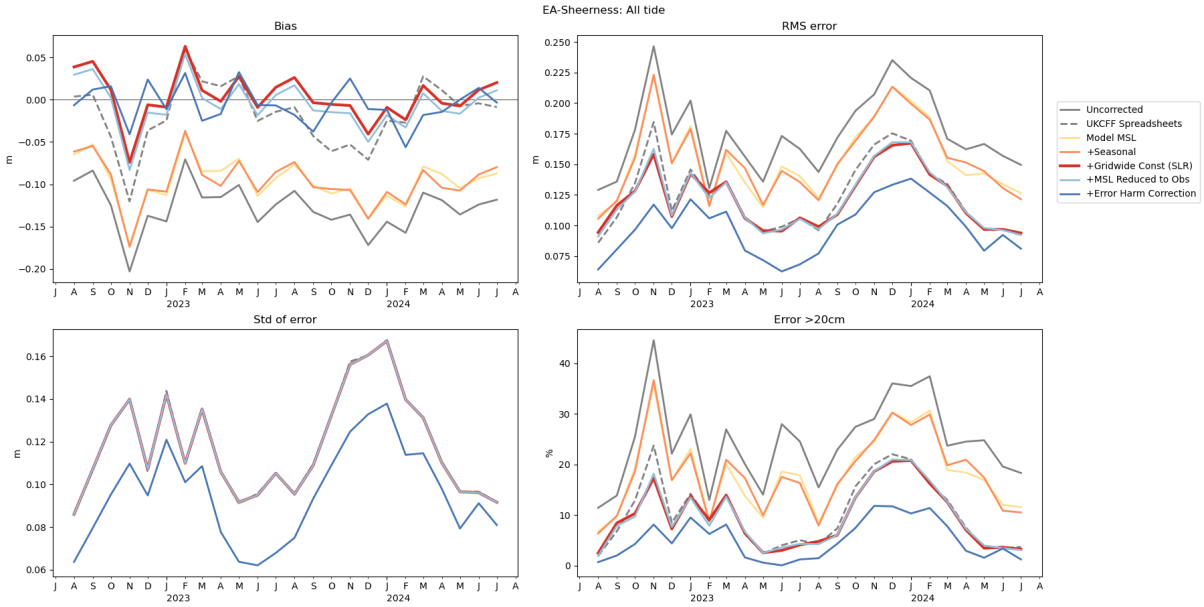

Figure 11: Monthly all-tide statistics at Sheerness for each correction experiment, from August 2022–July 2024

Similar plots for each class A tide gauge location are contained in Appendix A but will not be individually described here due to the large number of sites. Instead summary plots showing statistics for all ports and experiments are shown below. Figures 14–21 show the bias, RMS error, standard deviation of error, and X200 for each class A site for all times over the tidal cycle and the differences in these statistics compared with the original uncorrected forecast. Figures 22–29 are the same but for skew surge (ie high waters only). Panels from left to right show the uncorrected model, the previously suggested manual spreadsheet corrections, and then the five proposed automated corrections in the order described in

© Crown Copyright 2025, Met Office

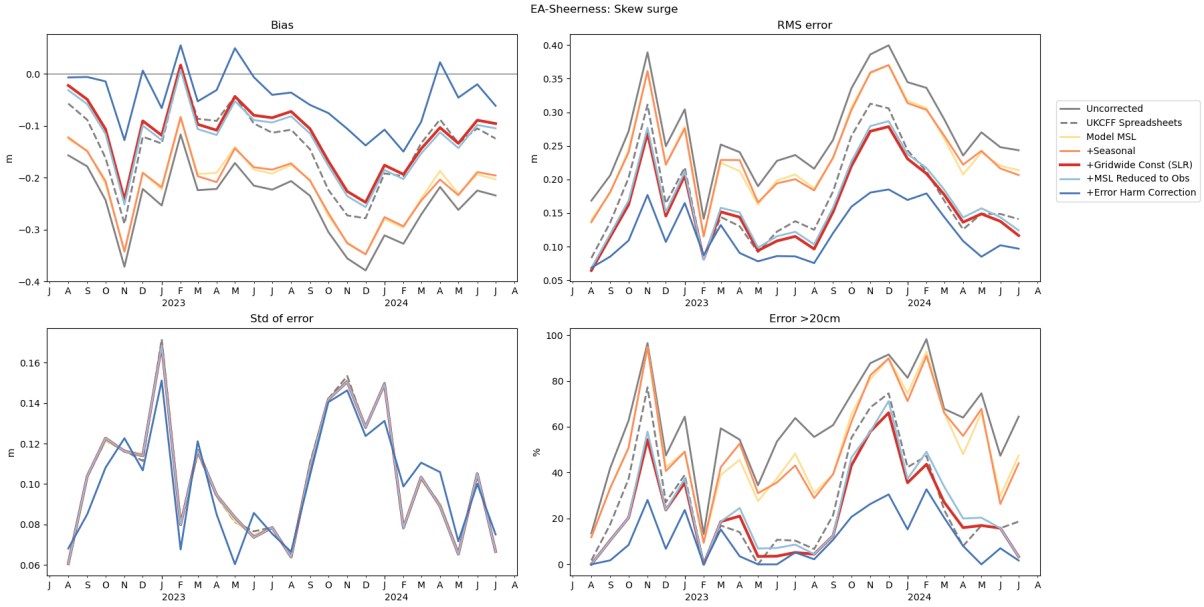

Figure 12: Monthly skew-surge statistics at Sheerness for each correction experiment, from August 2022–July 2024

table 1.

Immingham stands out as showing a significant and abrupt deterioration in the statistics in the summer of 2023. This is due to a shift in the tide gauge measurements, illustrated in Figure 13 which shows a running mean of the recorded water level over the 2 year period considered here. At the time of writing the gauge is awaiting a re-levelling assessment.

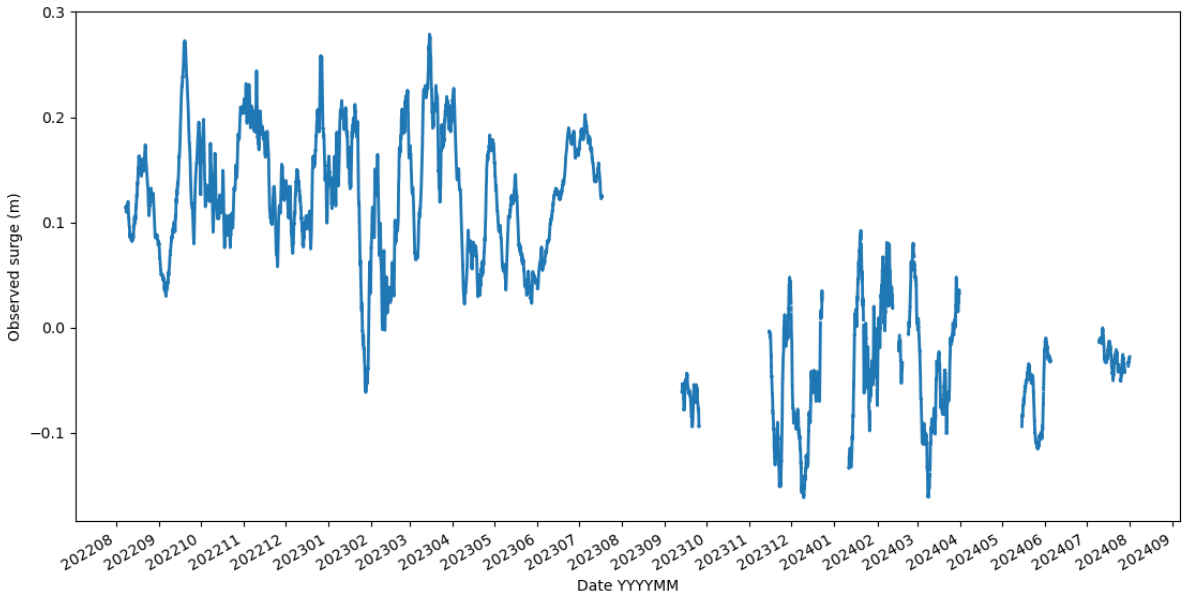

Figure 13: 7-day running average of observed surge residual at Immingham

The three upper Bristol Channel locations (Newport, Hinkley Point and Avonmouth) also stand out with relatively large errors compared to other areas, particularly after application of the full set of bias corrections. The tide is very complex in this region and is not a good fit to a harmonic series, leading

© Crown Copyright 2025, Met Office

to large errors in the harmonic tide prediction as seen in the case study example shown previously in Figure 6. The bias corrections applied here are not able nor intended to be able to address this type of error. The final correction, the harmonic error correction, does have more impact but again this is limited as it necessarily assumes that the shape of the error timeseries can be represented by a harmonic series.

Looking at the results as a whole, the plots show that the previously produced spreadsheet correction is effective at reducing error in almost all places. The standard deviation of the error is not significantly changed by the application of the spreadsheet, as would be expected as it does not change the shape of the forecast water level but moves it up or down en mass.

In the present study, three grid-wide adjustments have been applied in order to correct the model mean sea level spatially (north-south), temporally (seasonal), and uniformly (SLR). These corrections reduce model bias by allowing us to better approximate the true variation in mean sea level observed around the UK coast, and need to be applied together in order to be effective.

The spatial MSL correction on its own shows a strong geographic distribution with improvements in the southern locations and apparent deterioration in northern areas. This is because this spatially-varying MSL adjustment is only relevant when applied alongside the seasonal correction and SLR correction. The seasonal correction appears to improve the forecast in the summer period and decrease the performance in the winter, but the real benefit of this correction is that it makes the bias more consistent in time, which then allows the subsequent gridwide constant correction (for SLR) to be more effective.

After applying these three grid-wide corrections to better characterise the mean sea level in the model, the performance is generally significantly improved compared to the original uncorrected forecast. Overall the cumulative impact of applying corrections 1–3 (shown in the “+Gridwide Const (SLR)” panel in the figures) is in most cases similar to the impact of applying the previous manual spreadsheet corrections but with the advantage that it is applied across the whole model domain rather than being limited to the class A observation locations.

The two site-based corrections which use observation data (final two panels in figures 14–21) show that there is an improvement when applying them to the model, though the impact is strongest during the training period. The final correction, using harmonic series applied to the error, is the only method which has an impact on the error standard deviation, leading to a reduction in the standard deviation (ie a more predictable error) in most cases. However again this is most pronounced during the training period, and the impact in the second ‘unseen’ period is less.

© Crown Copyright 2025, Met Office

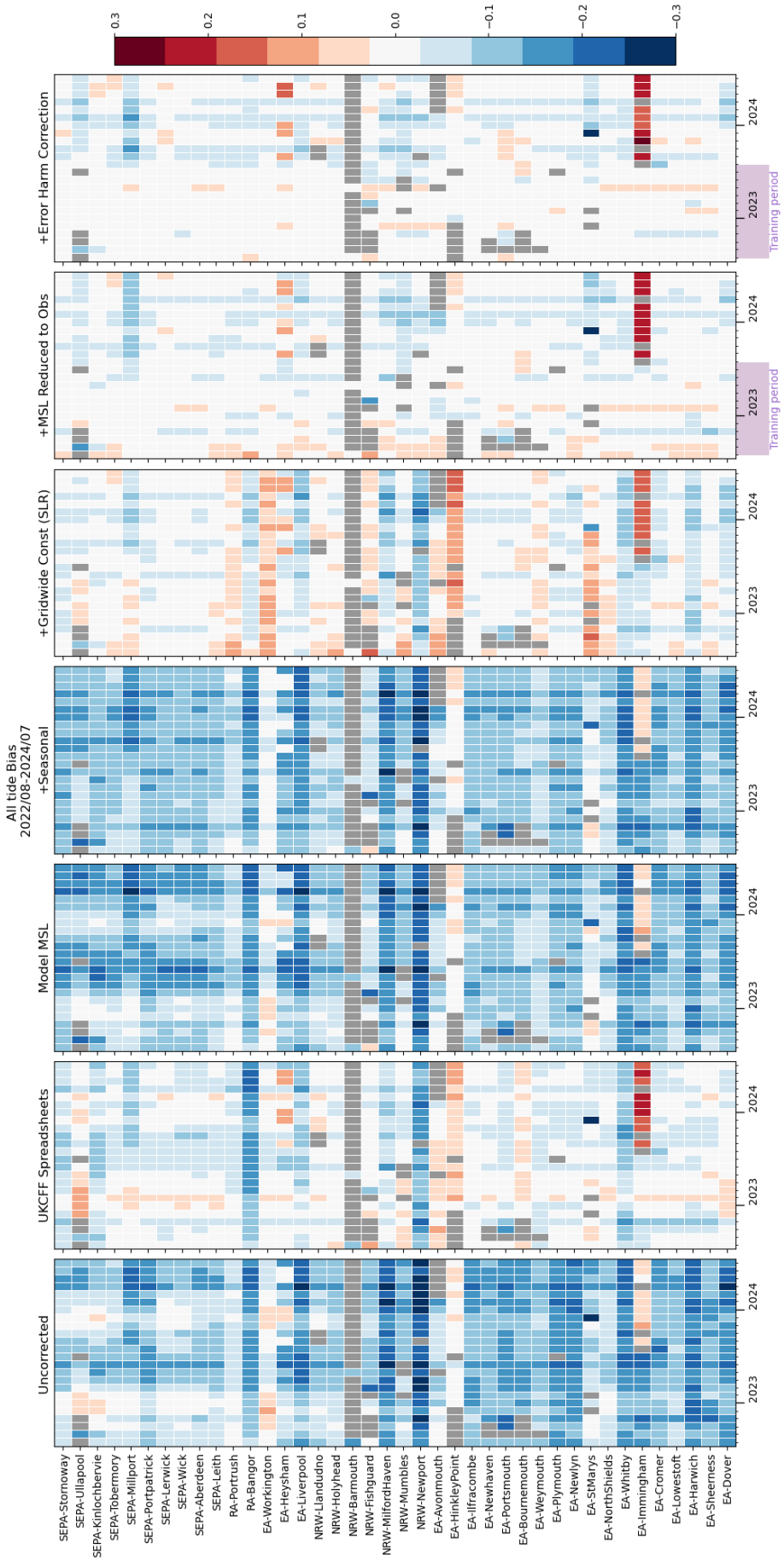

Figure 14: Bias in predicted water level at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

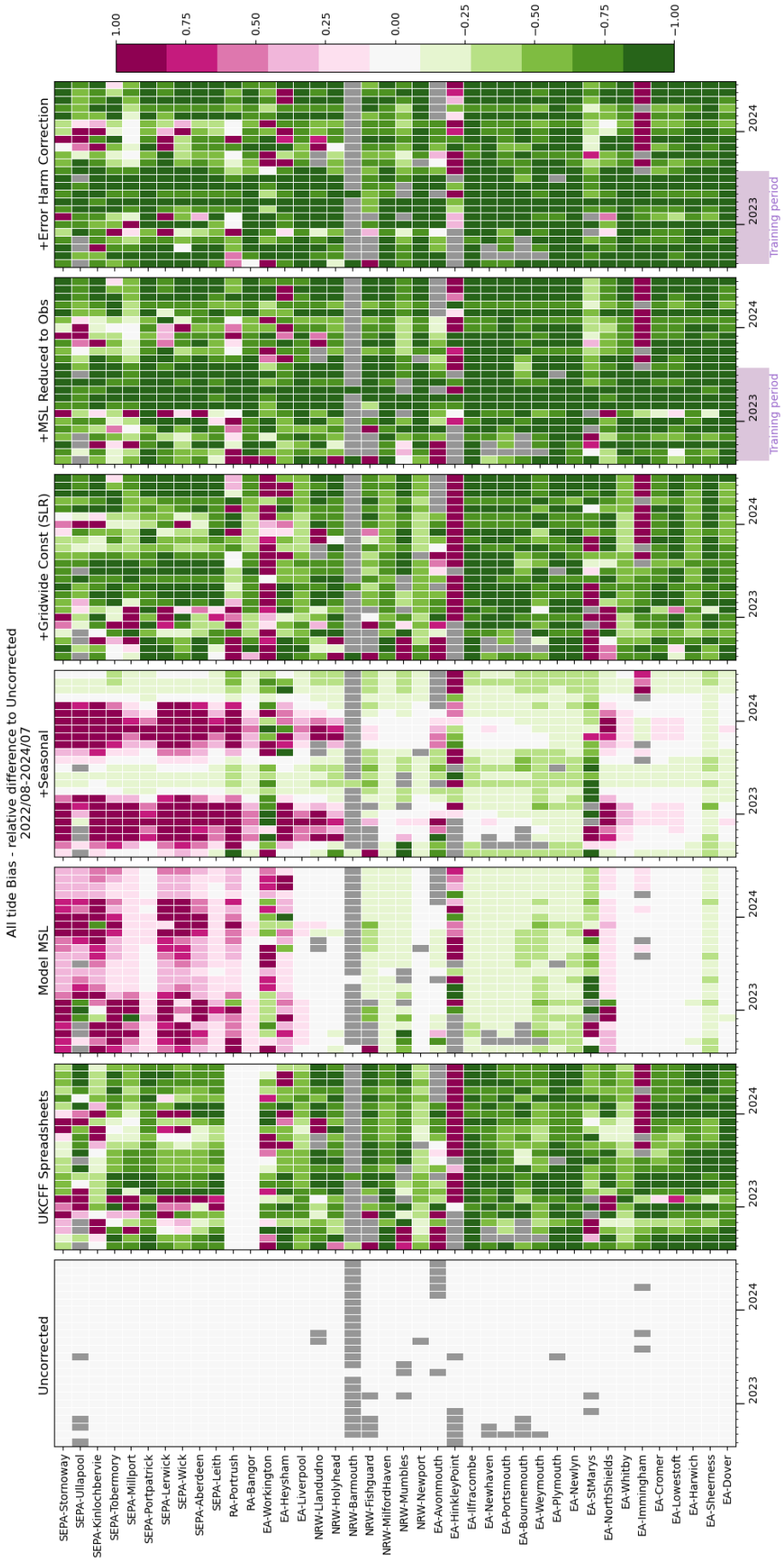

Figure 15: Relative difference, compared with the uncorrected forecast, in bias in predicted water level at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

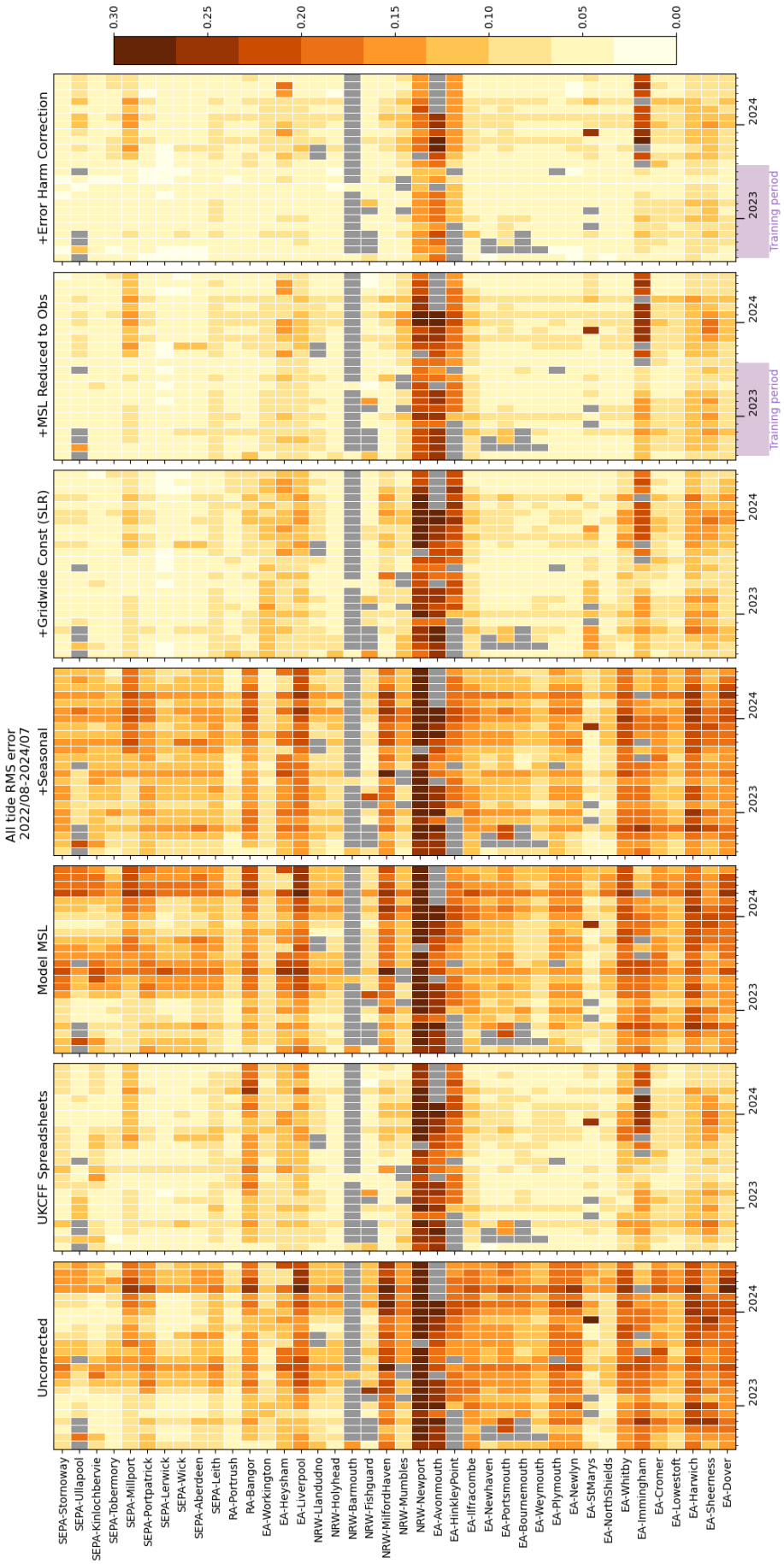

Figure 16: RMS error in predicted water level at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

Figure 17: Relative difference, compared with the uncorrected forecast, in RMS error in predicted water level at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

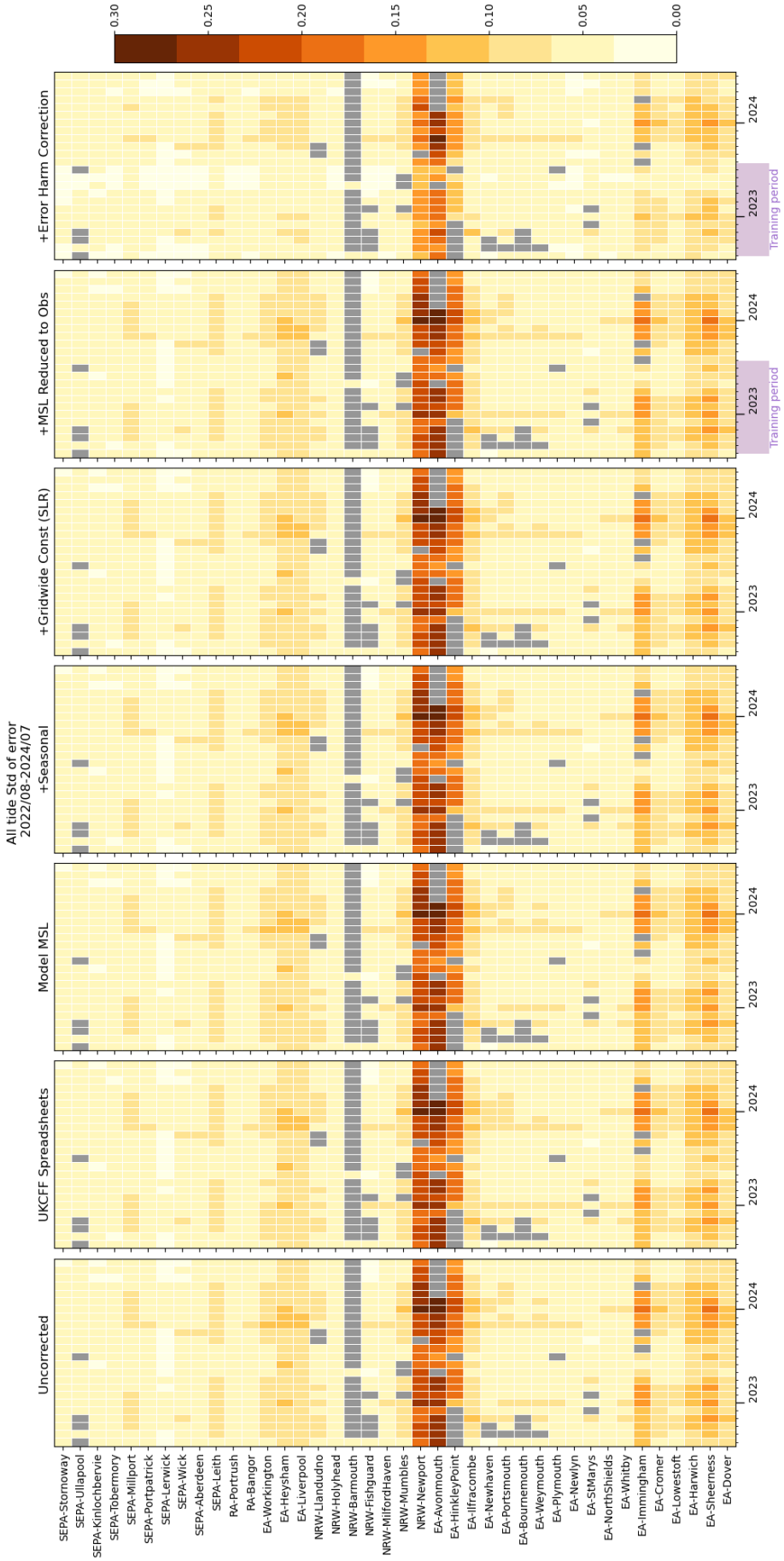

Figure 18: Standard deviation of error in predicted water level, compared with the uncorrected forecast, at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

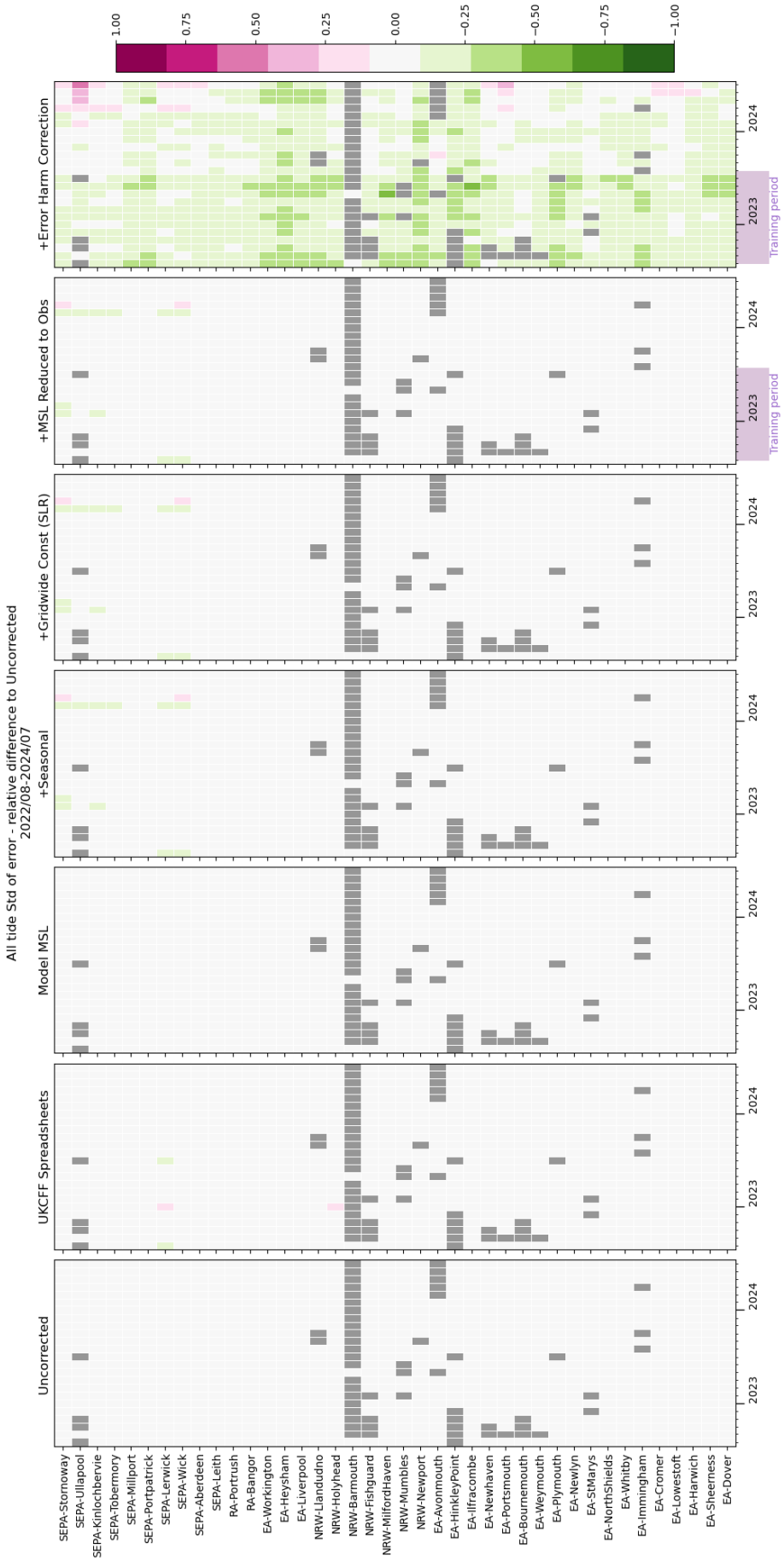

Figure 19: Relative difference, compared with the uncorrected forecast, in standard deviation of error in predicted water level at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

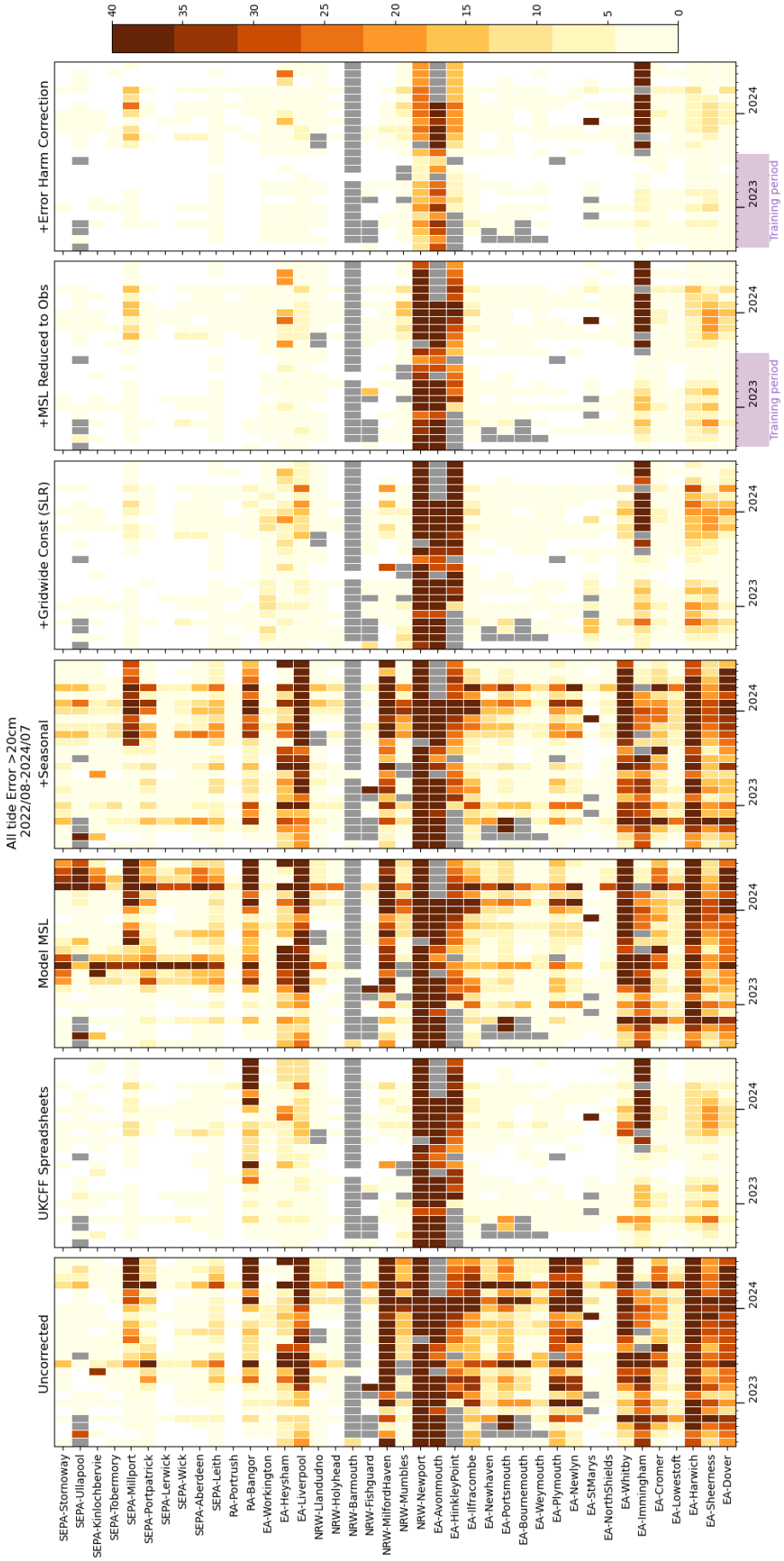

Figure 20: % of times error in predicted water level is more than 20 cm at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

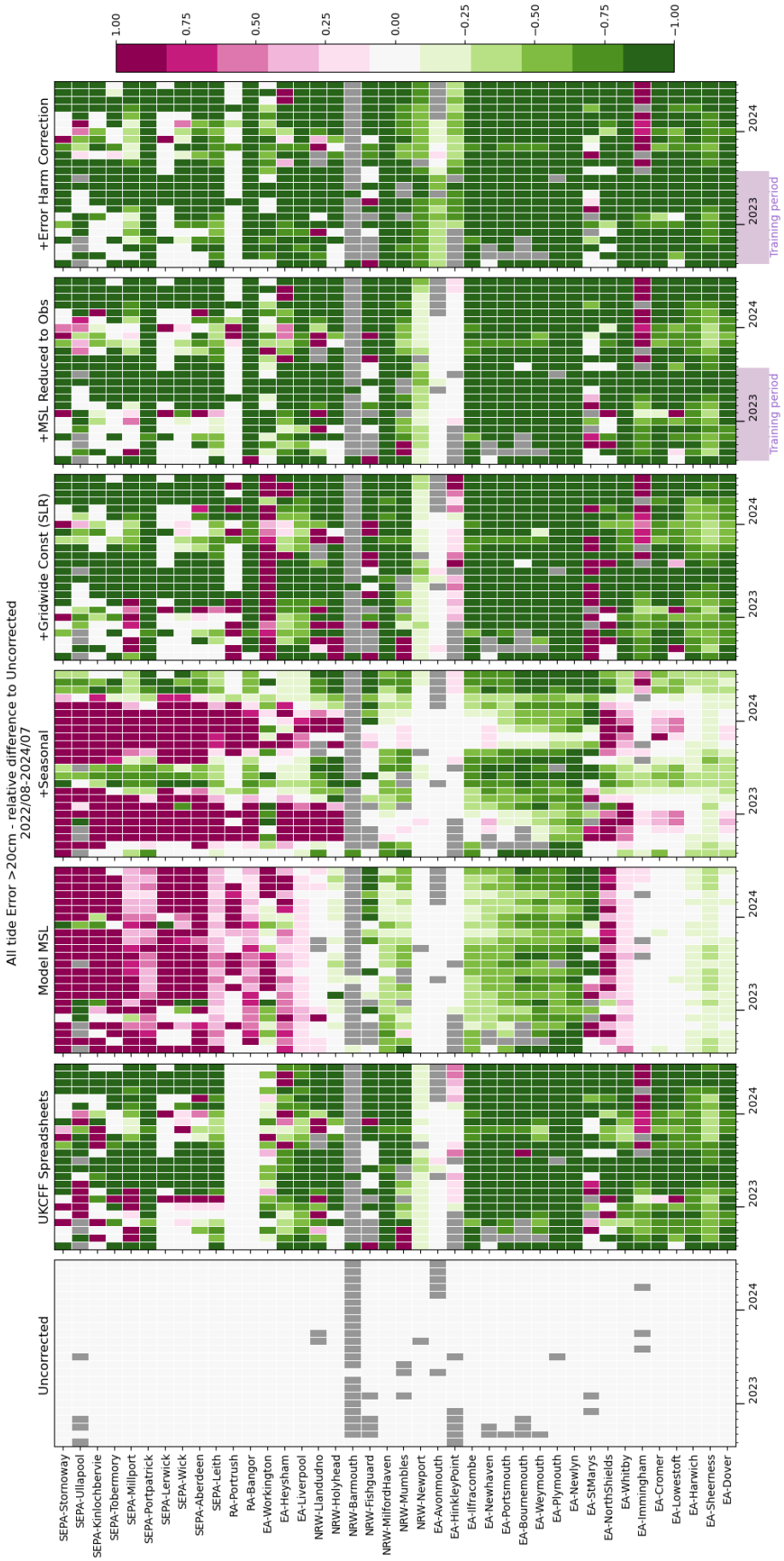

Figure 21: Relative difference, compared with the uncorrected forecast, in % of times the error in predicted water level is more than 20 cm at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

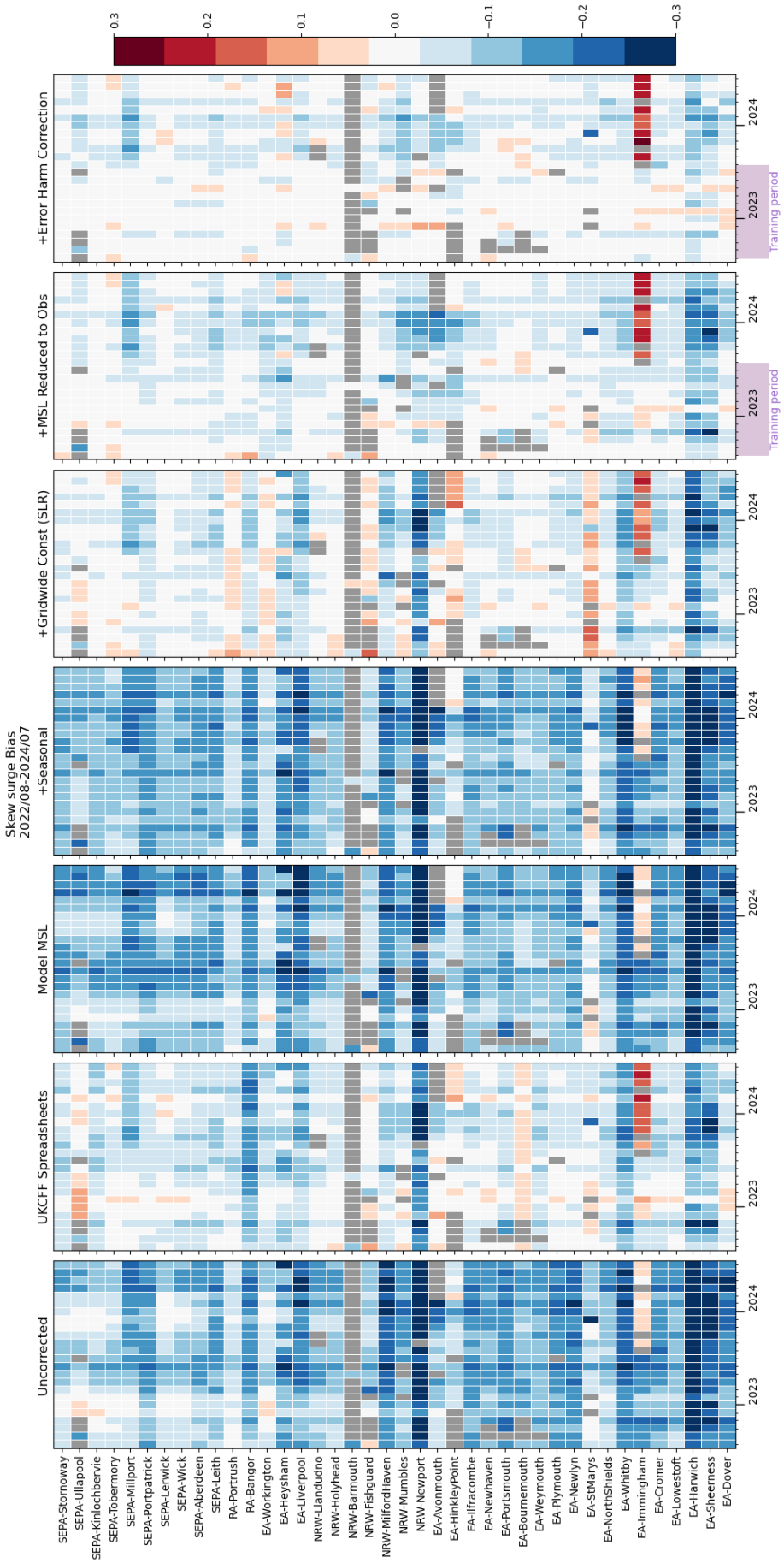

Figure 22: Bias in skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

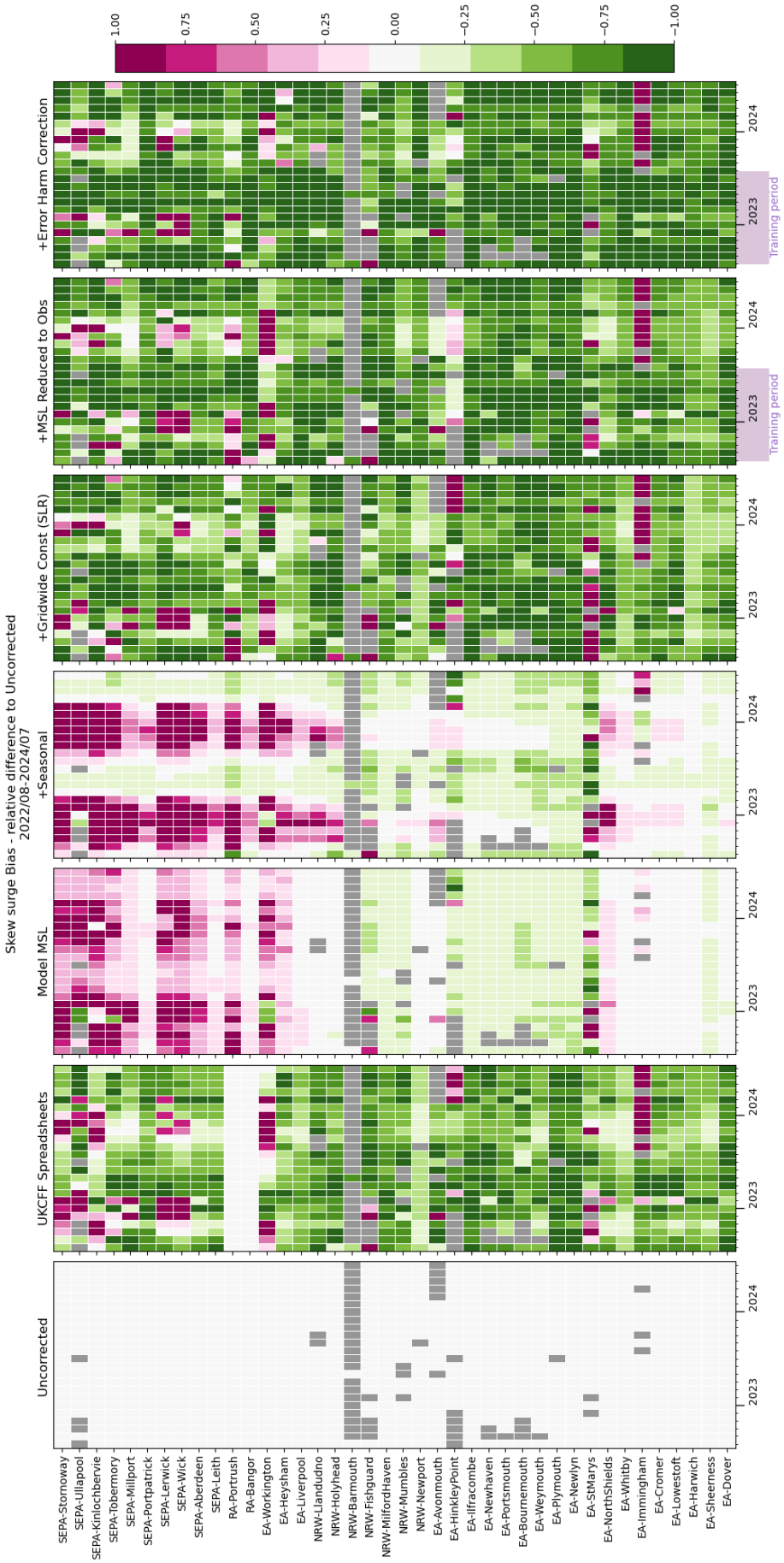

Figure 23: Relative difference, compared with the uncorrected forecast, in bias in skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

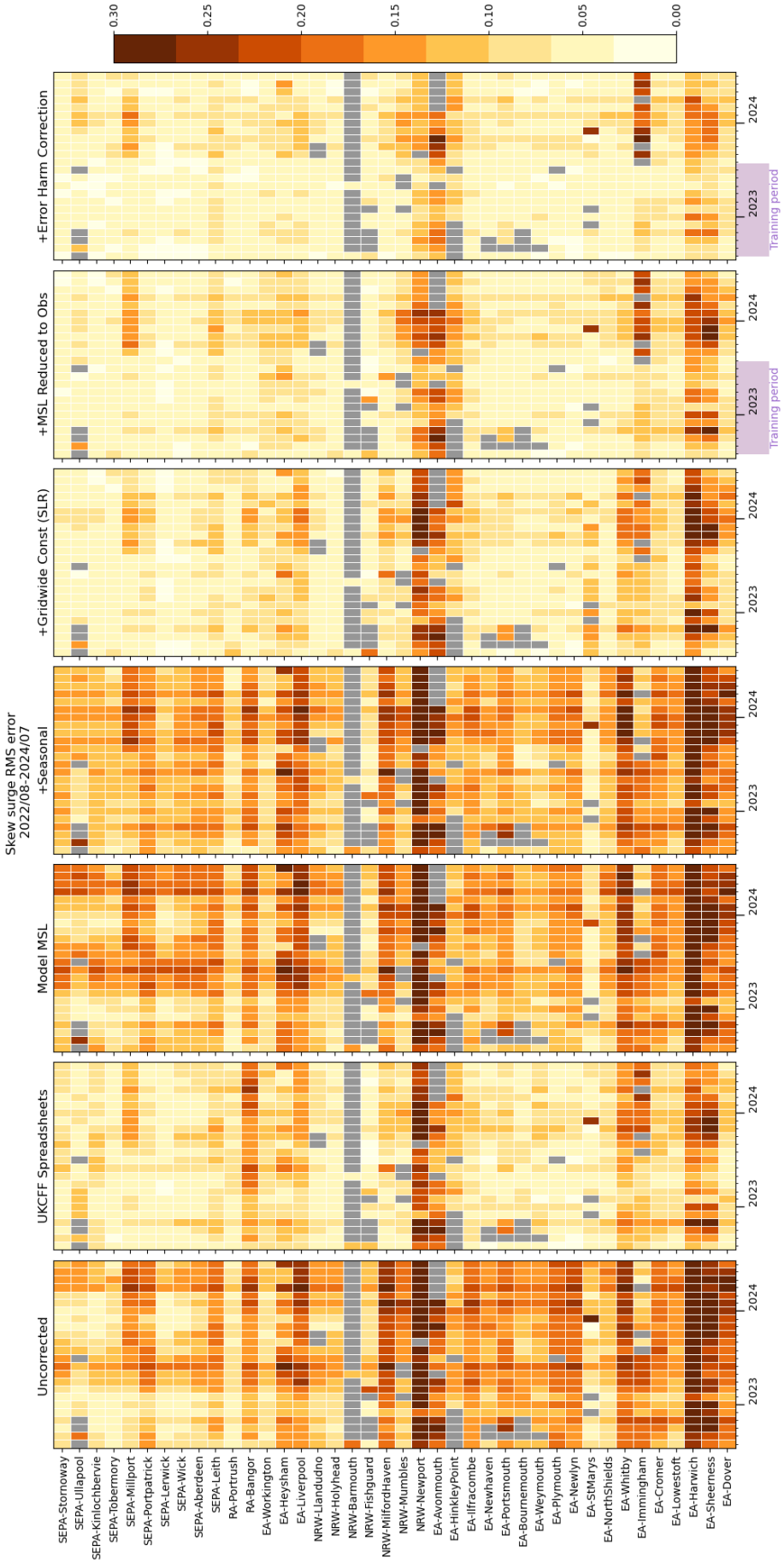

Figure 24: RMS error in skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

Figure 25: Relative difference, compared with the uncorrected forecast, in RMS error in skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

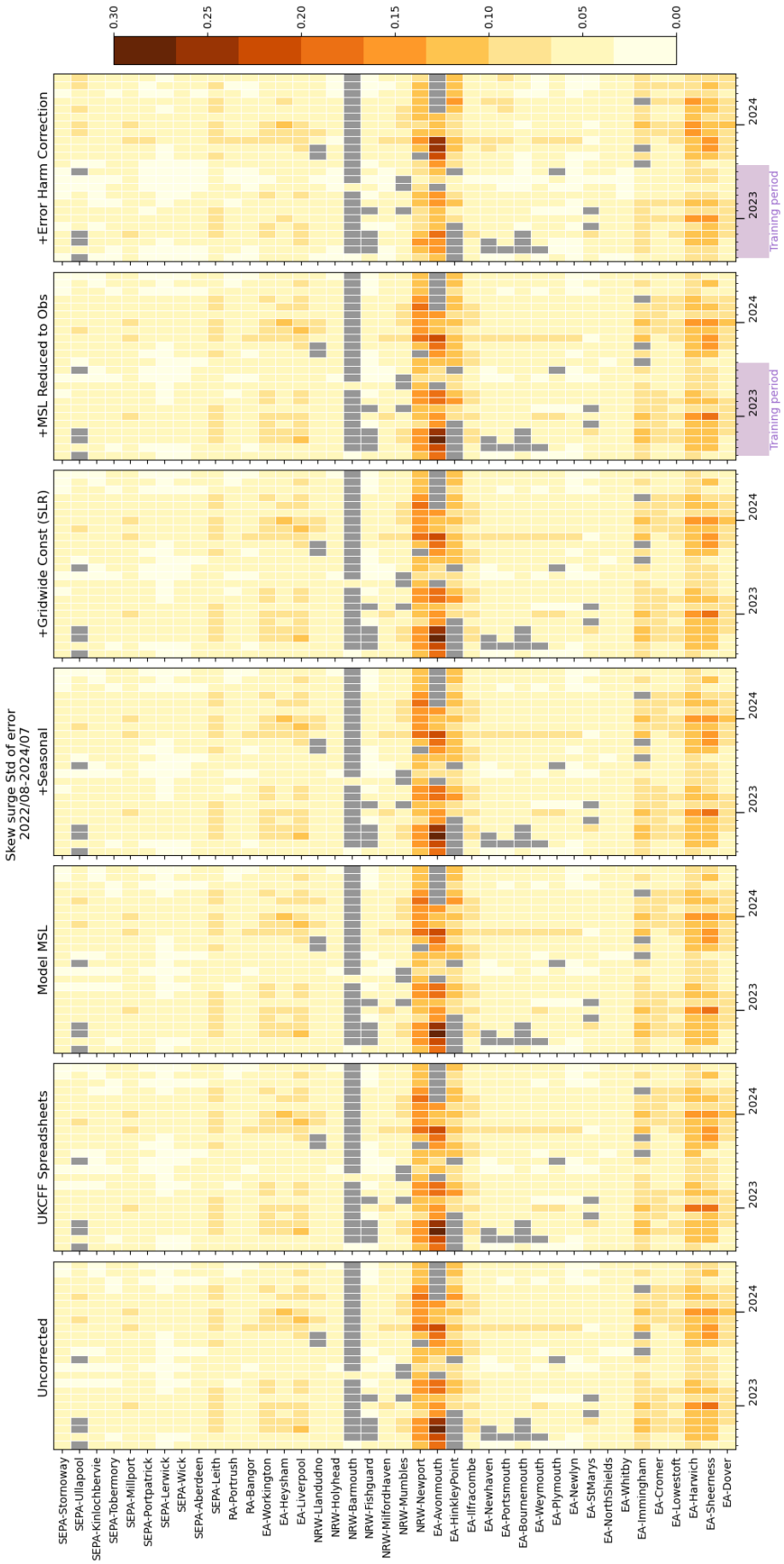

Figure 26: Standard deviation of error in skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

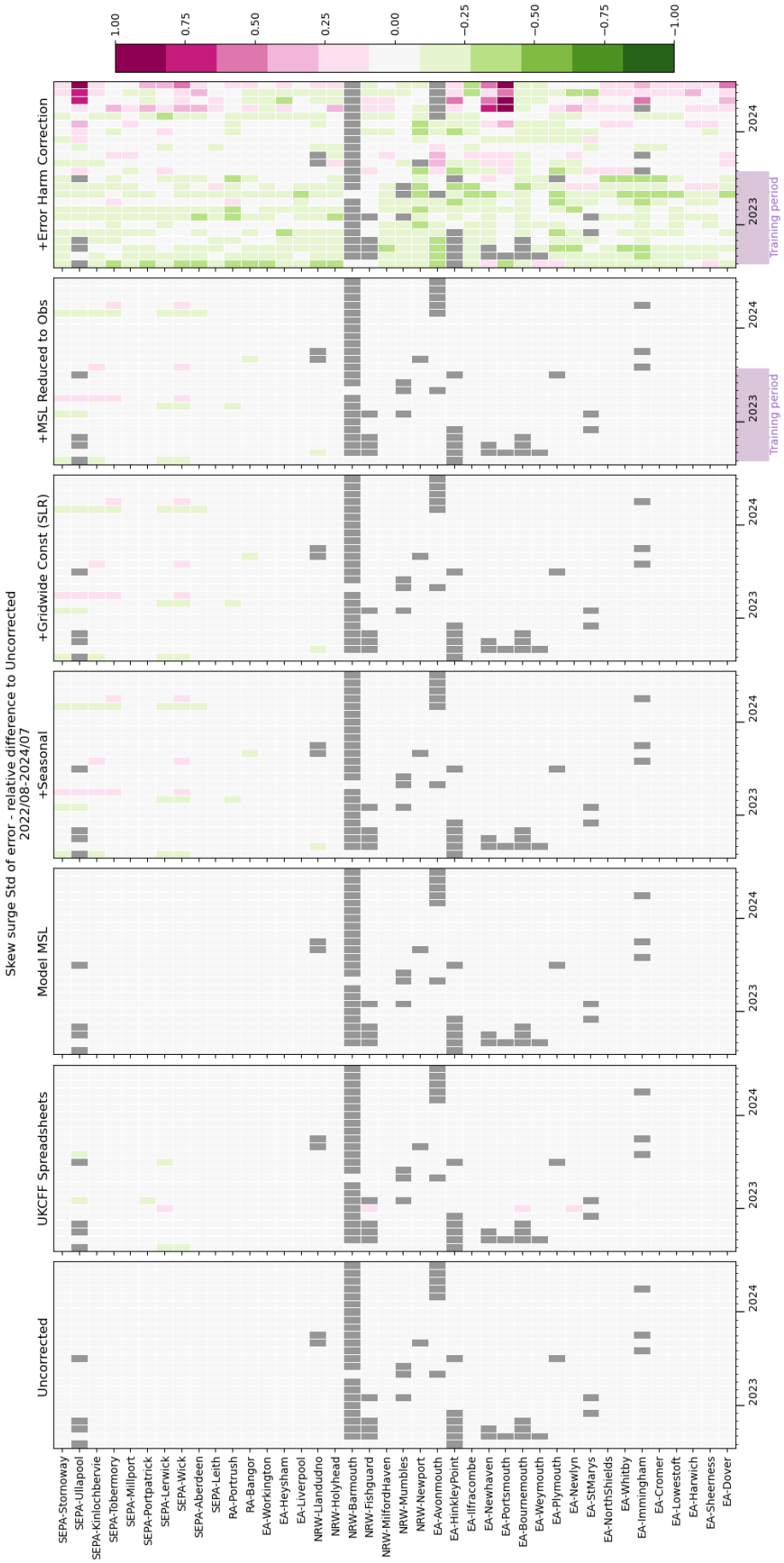

Figure 27: Relative difference, compared with the uncorrected forecast, in standard deviation of error in skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

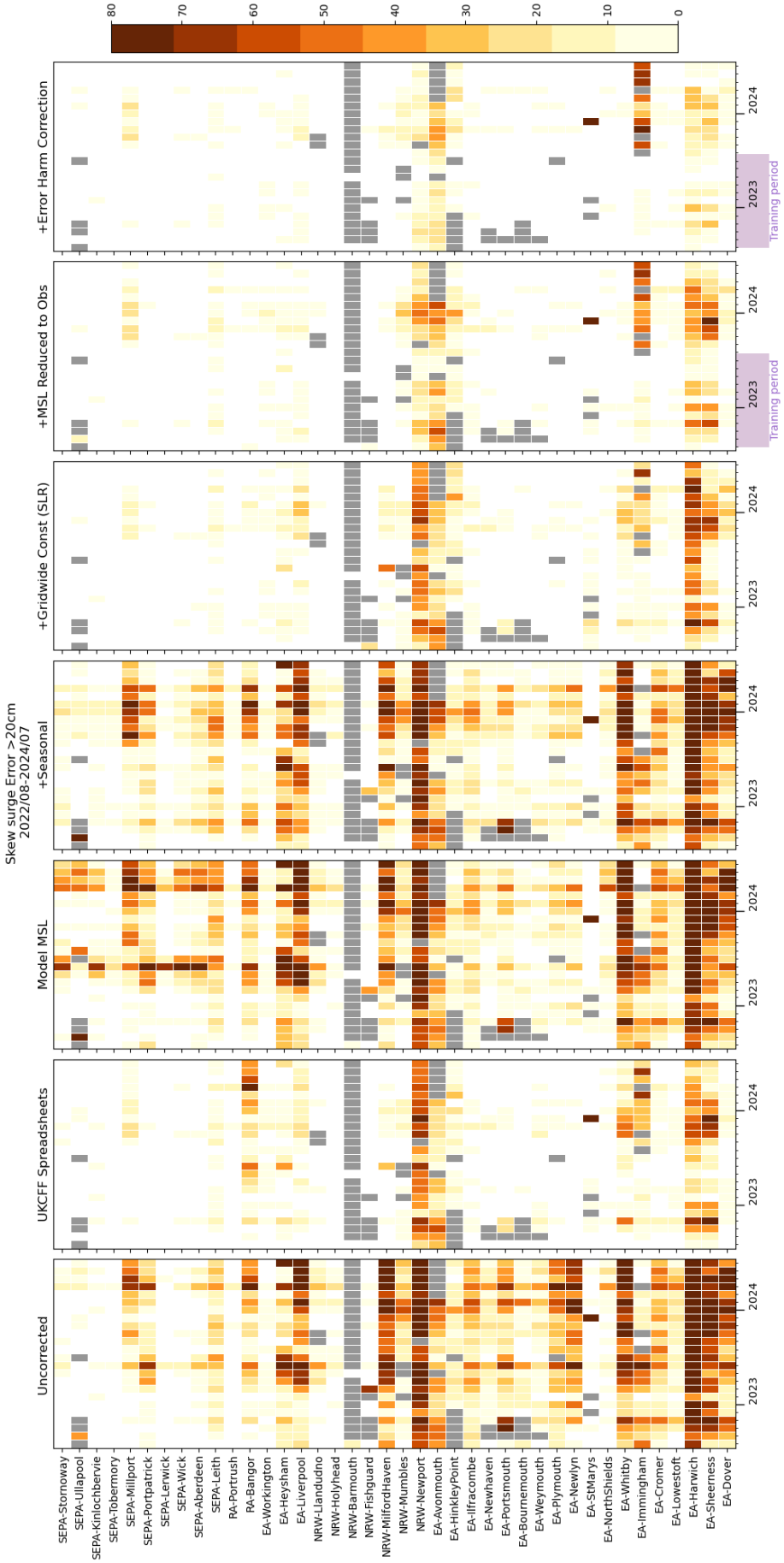

Figure 28: X200 for skew surge at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

Figure 29: Relative difference, compared with the uncorrected forecast, in % of times the error in skew surge is more than 20 cm at class A tide gauge locations for each correction experiment from August 2022–July 2024. Each coloured box represents one calendar month. Grey boxes indicate insufficient observation data.

© Crown Copyright 2025, Met Office

4 Conclusion and operational implementation

The results show that the water level forecast can be significantly improved using hindcast-derived bias correction to account for spatial and temporal differences in mean sea level. The level of improvement achieved by the grid-wide corrections is similar to that obtained by manually applying suggested spreadsheet corrections, but with the advantages that it is automated and can be applied to the whole model grid area rather than only at the class A tide gauge sites.

Although the use of harmonic analysis of past errors to construct an estimation of future errors improves the results further, it was decided not to implement it at this time due to the limited number of locations where it is available. Only bias corrections 1–3, i.e. those methods which are applied to the entire grid and do not rely on long observation timeseries at the forecast location, have been selected for operational implementation in this update. This is to ensure that the gridded and point-based product files which are provided to customers are consistent with each other and avoid the potential for confusion from different operational systems showing different forecasts.

The overall impact of this agreed correction scheme compared with the uncorrected forecast is summarised in Figures 30 to 35 which show the Bias, RMS error and X200 averaged over all of the Class A tide gauge sites as well as averaged over geographic regions. The sites included within each summary region are:

East Coast Lerwick, Wick, Aberdeen, Leith, North Shields, Whitby, Immingham, Cromer, Lowestoft, Harwich, Sheerness, Dover

South Coast Newlyn, Plymouth, Weymouth, Bournemouth, Portsmouth, Newhaven, Dover

West English Welsh Coast Ilfracombe, Hinkley Point, Avonmouth, Newport, Mumbles, Milford Haven, Fishguard, Barmouth, Holyhead, Llandudno, Liverpool, Heysham, Workington

West Scottish Coast and NI Portrush, Bangor, Portpatrick, Millport, Tobermory, Ullapool, Stornoway, Kinlochbervie

This agreed bias correction scheme was added to the operational production system on 29 August 2024.

The goal of these corrections is to address long-standing causes of bias within the operational surge forecast system and better centre the model predictions around the observed water levels, reducing the number of occasions where forecaster intervention is needed in most cases. The methods implemented at this stage do not change the fundamental behaviour or shape of the predicted surge so additional correction, such as manual forecaster intervention or the NOC ‘astro-re-engineering’ error correction tool (Hibbert et al., 2015), may still be needed at high water in some locations. Guidance on this has been issued as a note to forecasters. There are a number of estuary locations around the UK coast (for example the Thames and Severn estuaries) where the present surge forecasting approach (harmonic tide plus modelled surge) cannot adequately capture the large, asymmetric estuary tides. The present

© Crown Copyright 2025, Met Office

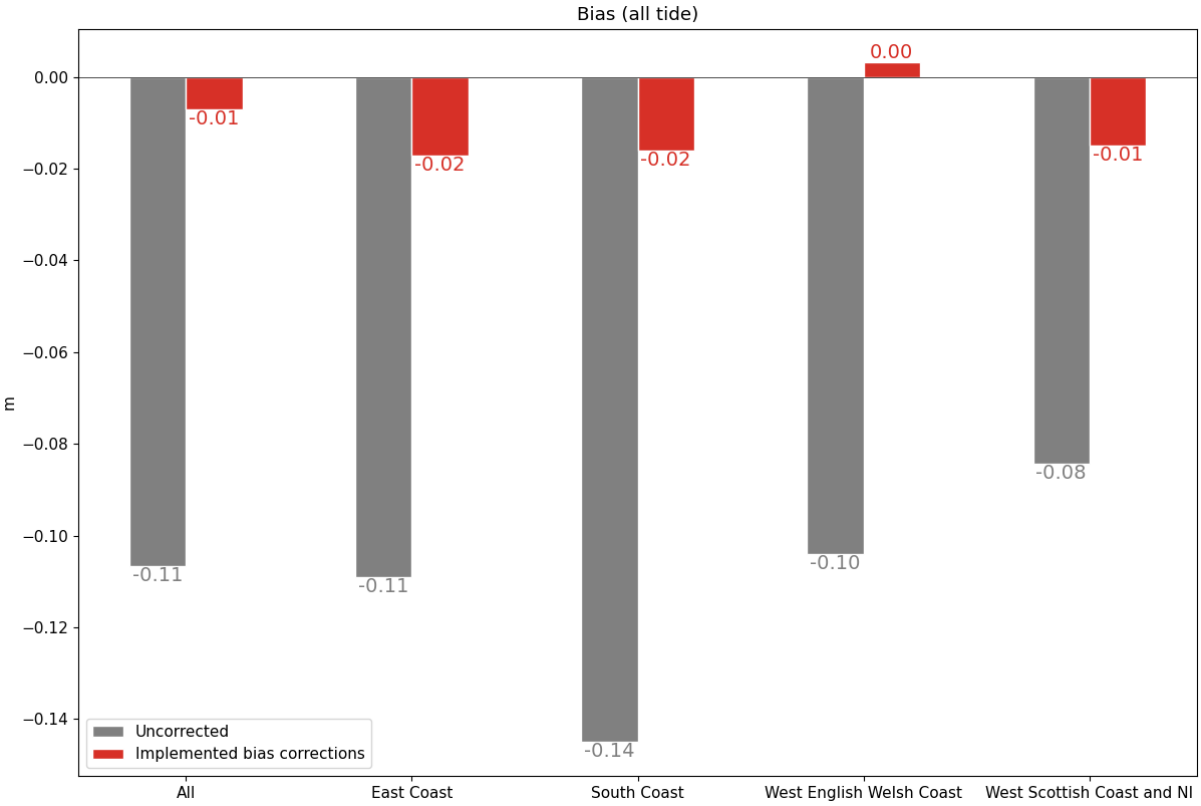

Figure 30: Mean bias over all tide cycle

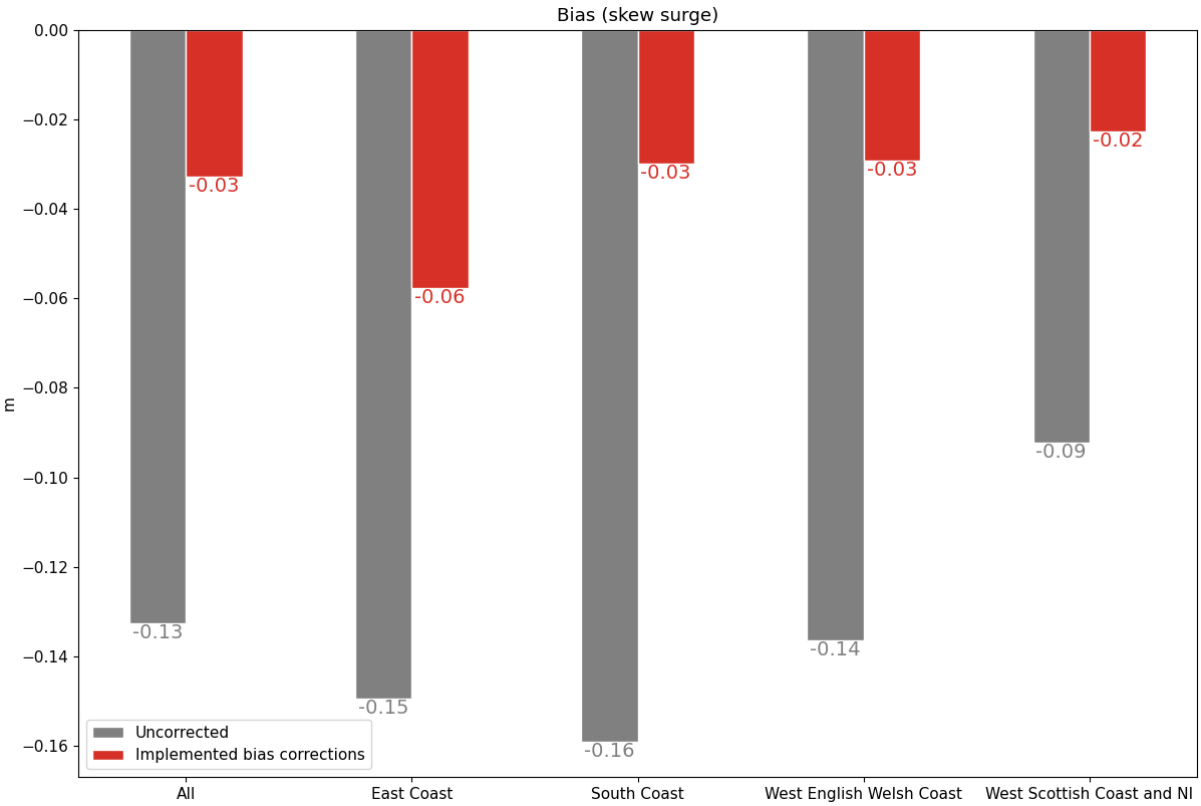

Figure 31: Mean bias over high waters only

© Crown Copyright 2025, Met Office

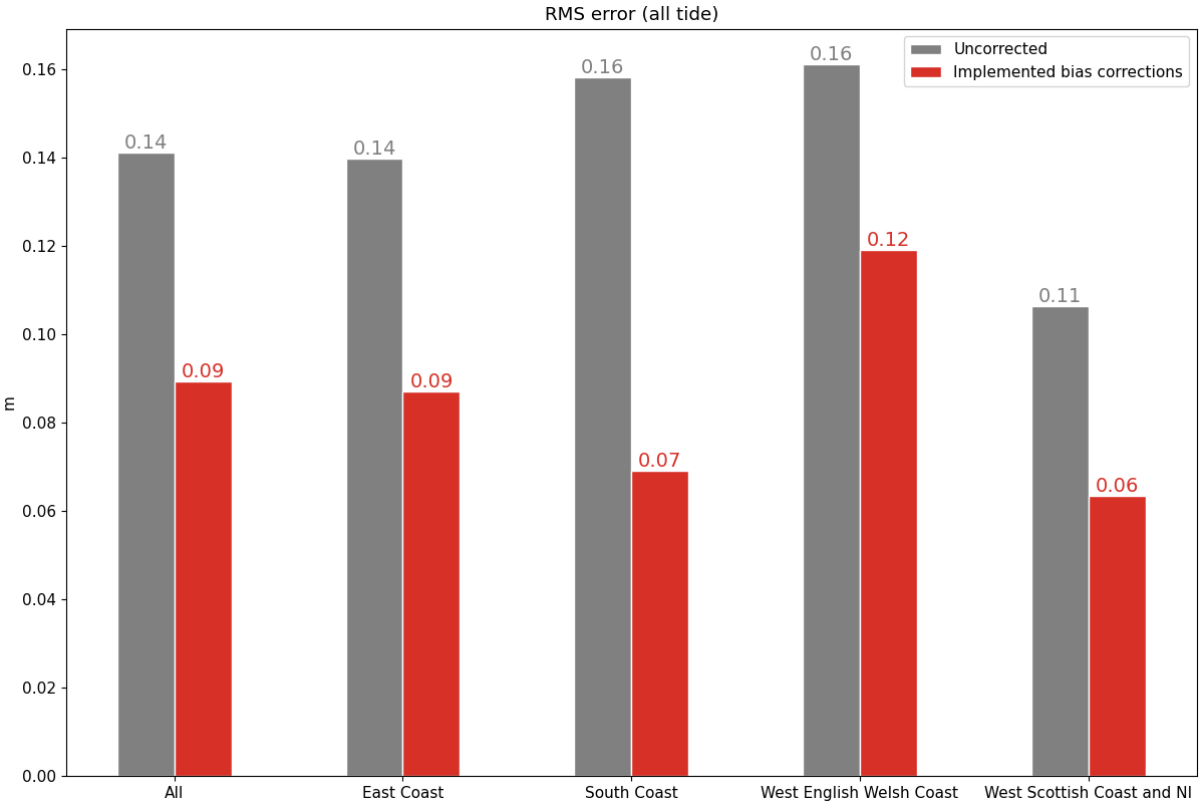

Figure 32: Mean RMS error over all tide cycle

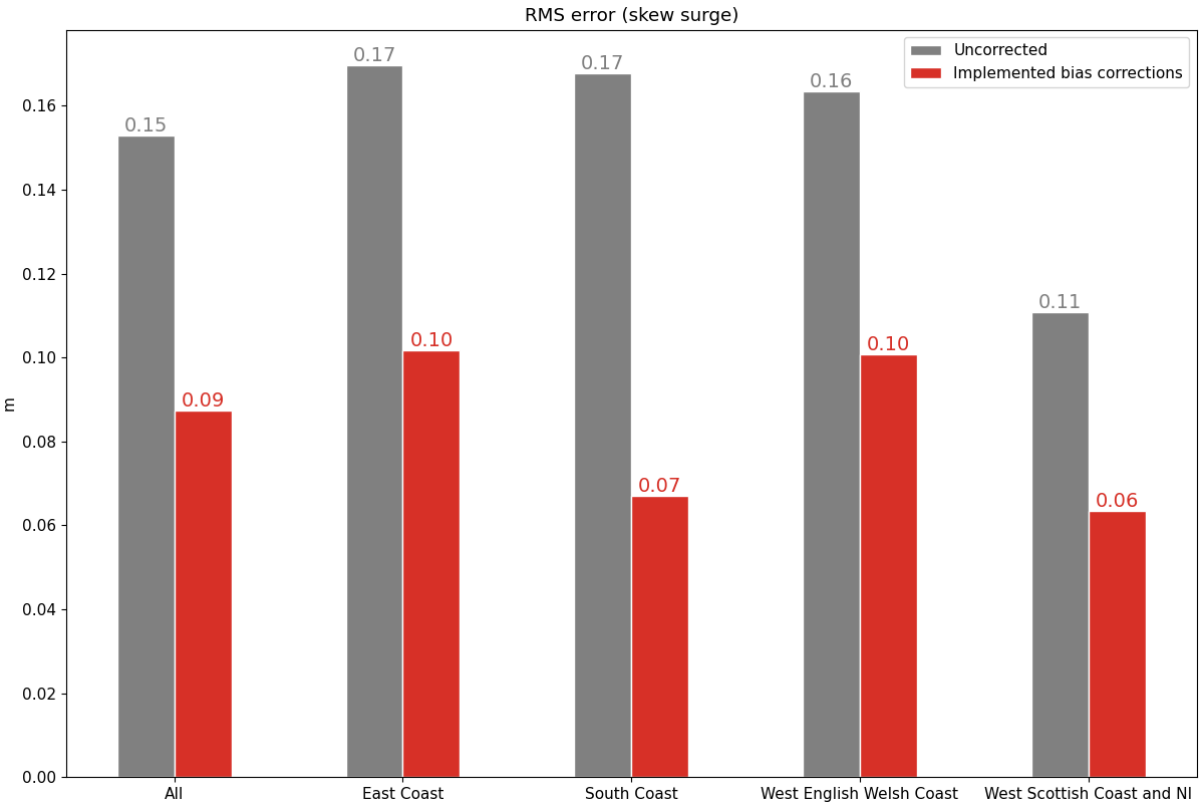

Figure 33: Mean RMS error over high waters only

© Crown Copyright 2025, Met Office

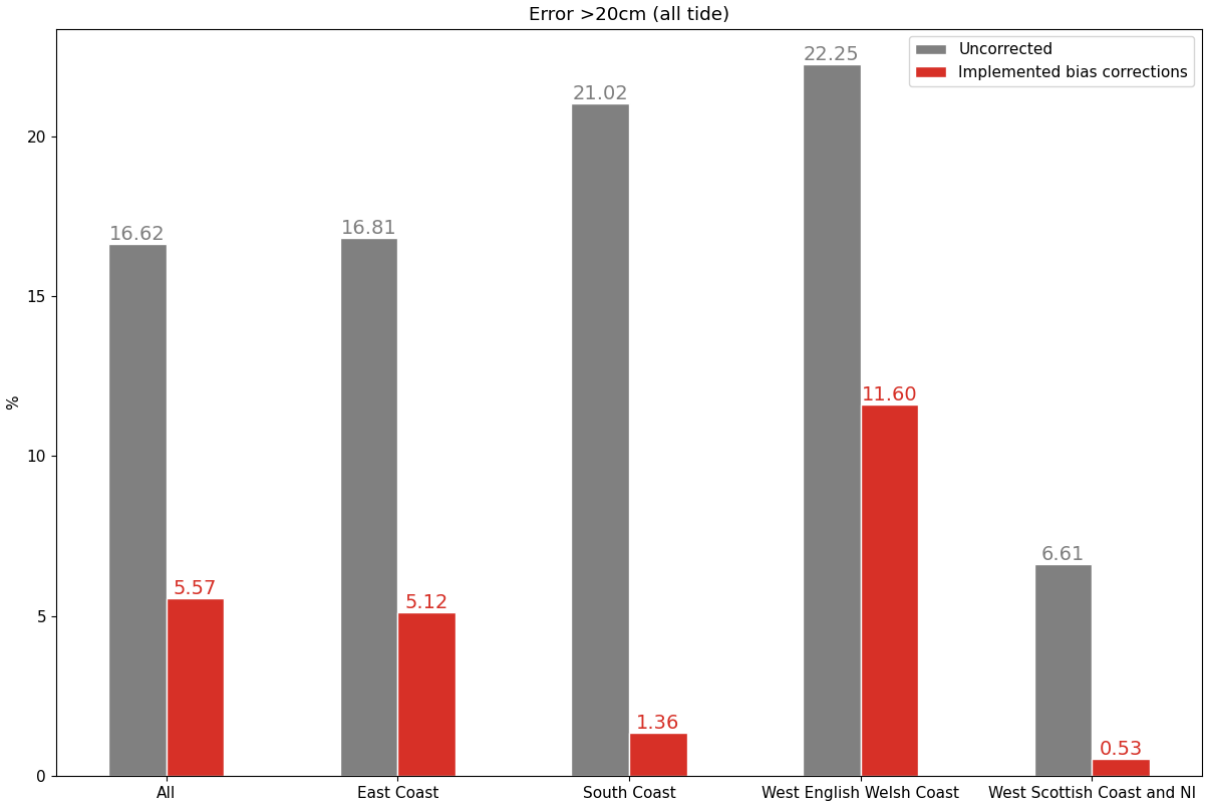

Figure 34: Mean X200 score over all tide cycle

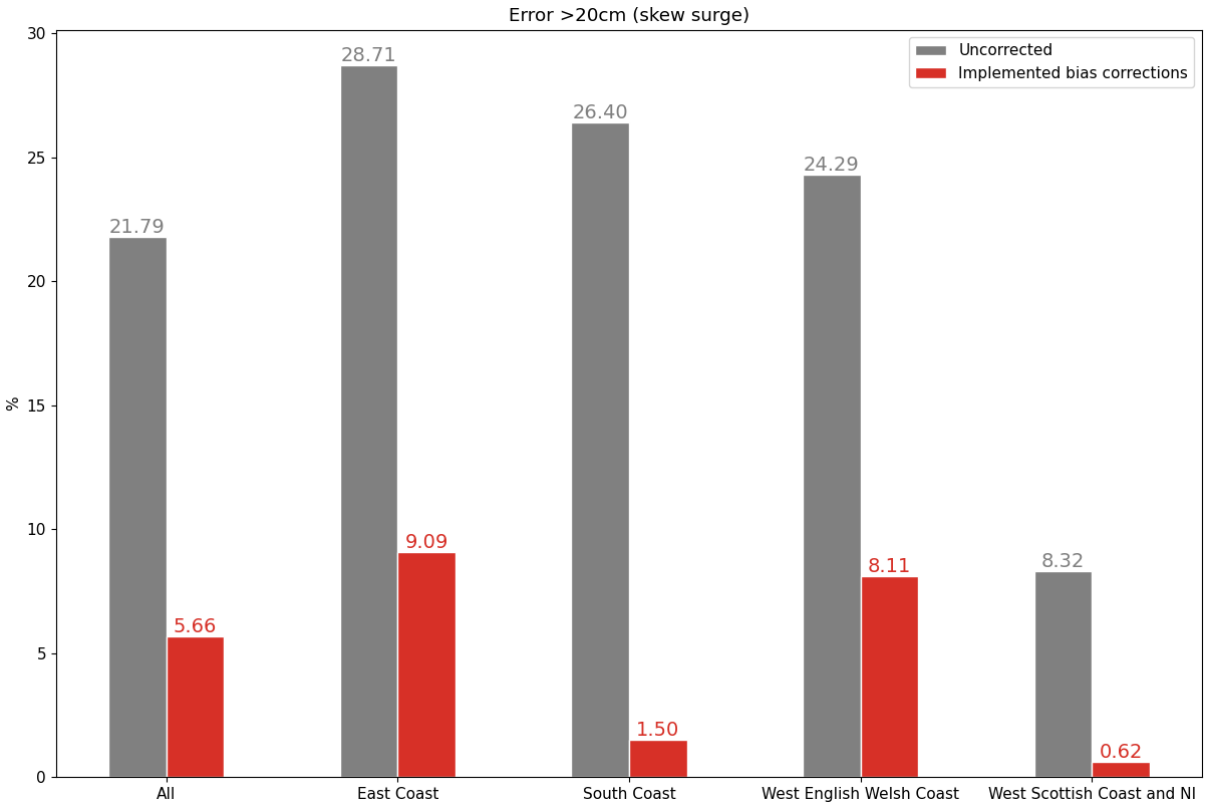

Figure 35: Mean X200 score over high waters only

© Crown Copyright 2025, Met Office

bias correction work is not expected or intended to correct for these less systematic sources of error in the methodology. These will instead be addressed in future methodological improvement work planned over the coming years

In order to ensure that the bias correction remains up to date, the Met Office proposes a future schedule in which the gridwide constant correction is reviewed and updated annually using the most recent available observation verification data to account for interannual variability in mean sea level. Additionally it is desirable to update the hindcast annually to include the full previous winter period (noting that ERA5 forcing is available several months in arrears), to allow the MSL and seasonal corrections to be updated. However these are not expected to change significantly from year to year so this step is considered non-essential.

The updated bias corrections will be calculated and released in the summer in good time for the winter season. Additionally, outside of this schedule, the corrections may need to be re-evaluated to adjust for other improvements or changes to the forecast system. For example if the harmonic tide predictions are altered in future to account for the radiational tides then correction 2 would no longer be required.

Any updates to the bias correction or other parts of the forecast system will be scheduled in advance and agreed with users through the UK Coastal Flood Forecasting technical group.

5 Use of the surge hindcast

It is not proposed to add these bias corrections to the hindcast dataset as it would not be appropriate for all potential uses of the data. Keeping the hindcast dataset in its raw format will ensure it is as flexible as possible for use in different applications.

For example the seasonal and grid-constant corrections applied to the forecast are specific to the current operational use case of adding the model surge residual to an observation-derived harmonic tide prediction. For applications that use the model total water level instead, these corrections would not be appropriate.

The gridwide constant correction is based on model performance compared with recent observations, so this correction would also not be suitable to apply to the entire 40 years of the hindcast as it is likely to change significantly over that period of time.

The corrections will be made available with the hindcast so that users can apply them as appropriate for their specific use case.

© Crown Copyright 2025, Met Office

References

Flather, R., Williams, J., and Blackman, D. (2000), Causes of seasonal sea level variations and implications for surge prediction, *Tech. rep.*, Proudman Oceanographic Laboratory [now NOC], issue: 136.

Hersbach, H., et al. (2020), The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049, DOI: 10.1002/qj.3803 . URL: https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803.

Hibbert, A., Royston, S.J., Horsburgh, K.J., Leach, H., and Hisscott, A. (2015), An empirical approach to improving tidal predictions using recent real-time tide gauge data, *Journal of Operational Oceanography*, *8*(1), 40–51, DOI: 10.1080/1755876x.2015.1014641 , publisher: Taylor & Francis.

O'Neill, C., and Saulter, A. (2017), NEMO-Surge : Forecast performance during 2016-2017 winter trial, *Tech. rep.*, Met Office. URL: https://digital.nmla.metoffice.gov.uk/IO_06960ecc-e39f-4b0d-934b-643f55a45ab6/, issue: August.

O'Neill, C., Saulter, A., Williams, J., and Horsburgh, K. (2016), NEMO-surge: Application of atmospheric forcing and surge evaluation, *Tech. rep.*, Met Office, issue: December.

Williams, J., Irazoqui Apecechea, M., Saulter, A., and Horsburgh, K.J. (2018a), Radiational tides: Their double-counting in storm surge forecasts and contribution to the Highest Astronomical Tide, *Ocean Science*, *14*(5), 1057–1068, DOI: 10.5194/os-14-1057-2018 .

Williams, J., Saulter, A., O'Neill, C., Brown, J., and Horsburgh, K. (2018b), A reassessment of the UK operational surge forecasting procedure [2018], *Tech. rep.*, National Oceanography Centre, Southampton. URL: https://nora.nerc.ac.uk/id/eprint/519017/.

© Crown Copyright 2025, Met Office

Appendix A Statistics timeseries for all class A sites

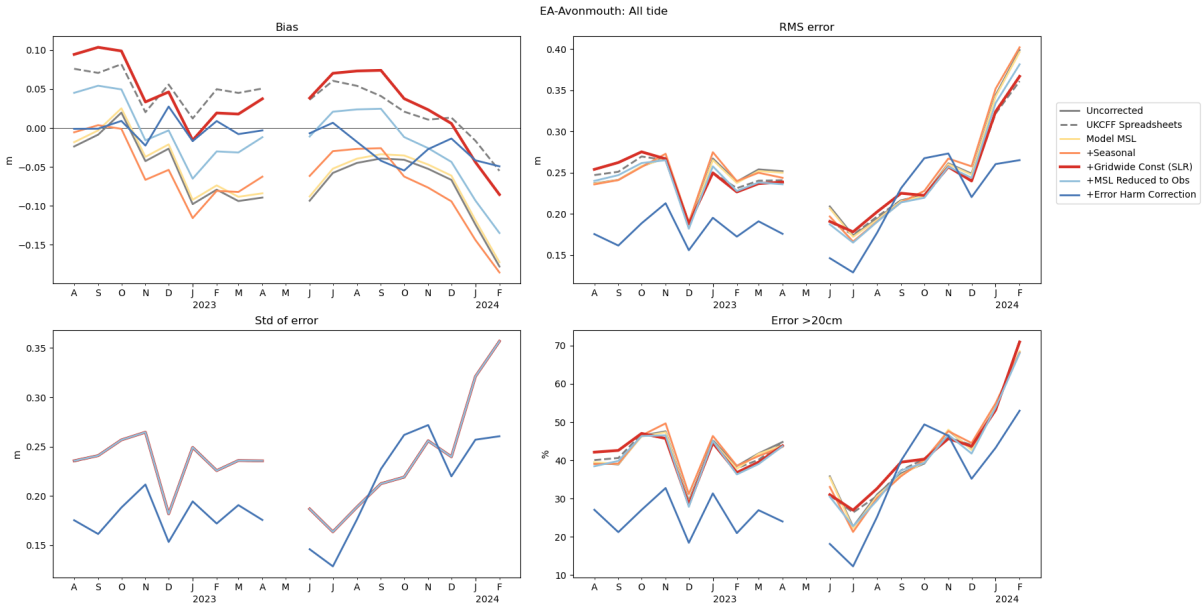

Figure A.1: All tide statistics for site EA-Avonmouth from August 2022–July 2024

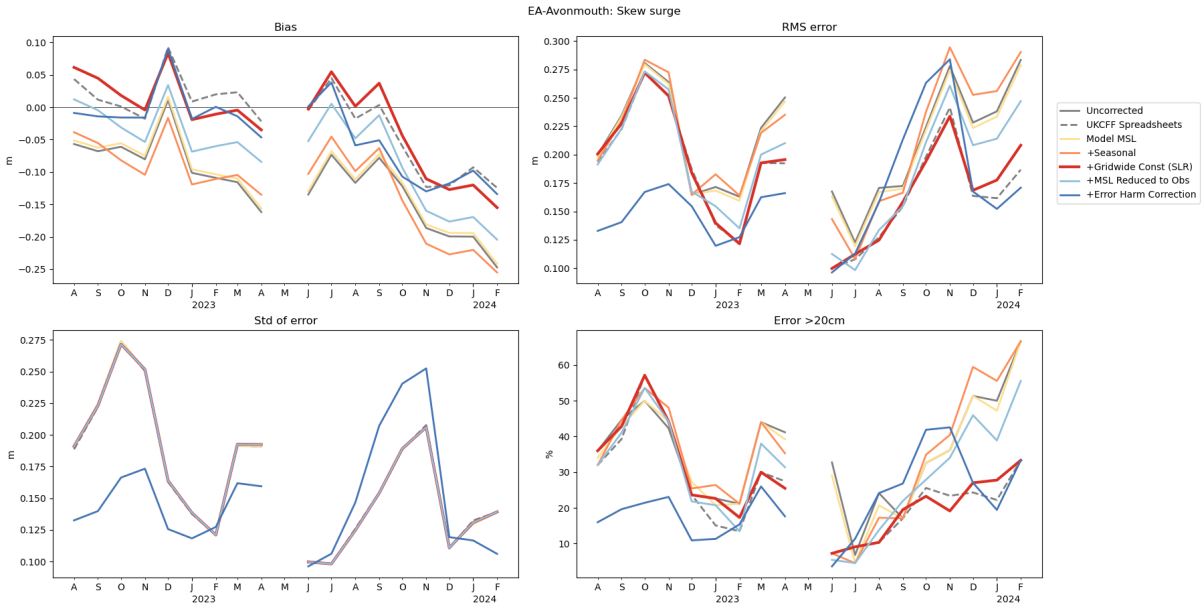

Figure A.2: Skew surge statistics for site EA-Avonmouth from August 2022–July 2024

© Crown Copyright 2025, Met Office

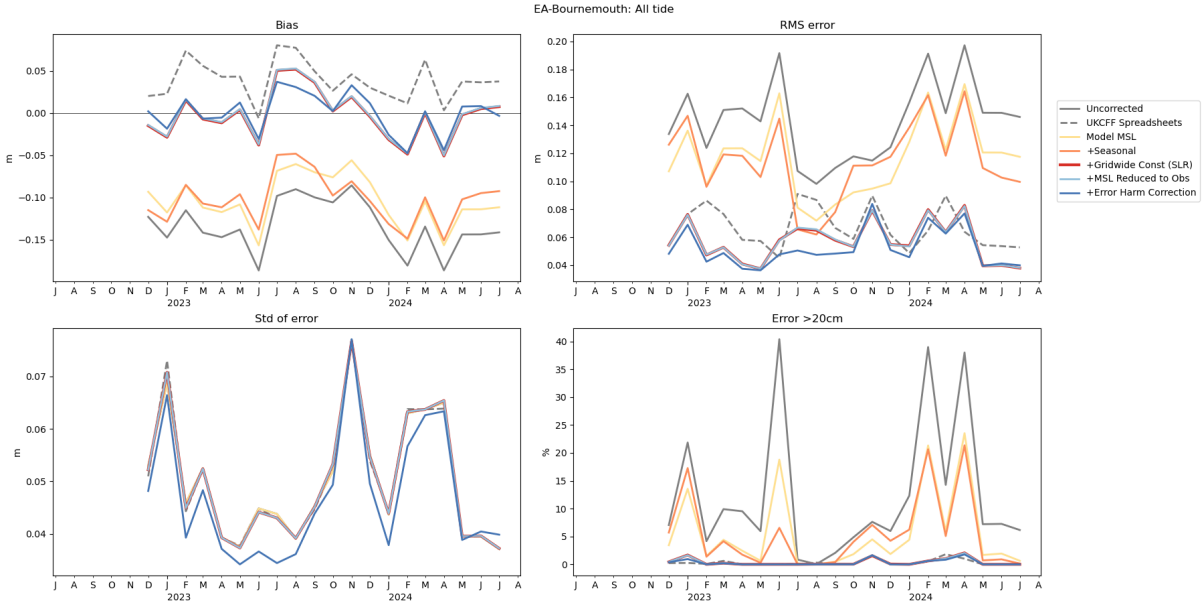

Figure A.3: All tide statistics for site EA-Bournemouth from August 2022–July 2024

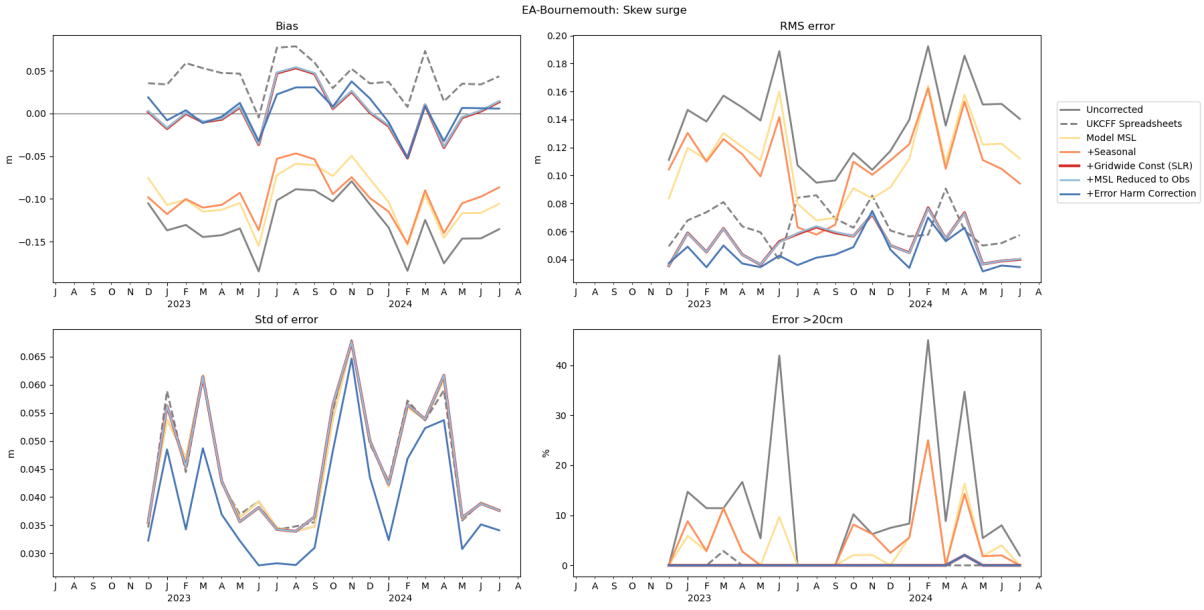

Figure A.4: Skew surge statistics for site EA-Bournemouth from August 2022–July 2024

© Crown Copyright 2025, Met Office

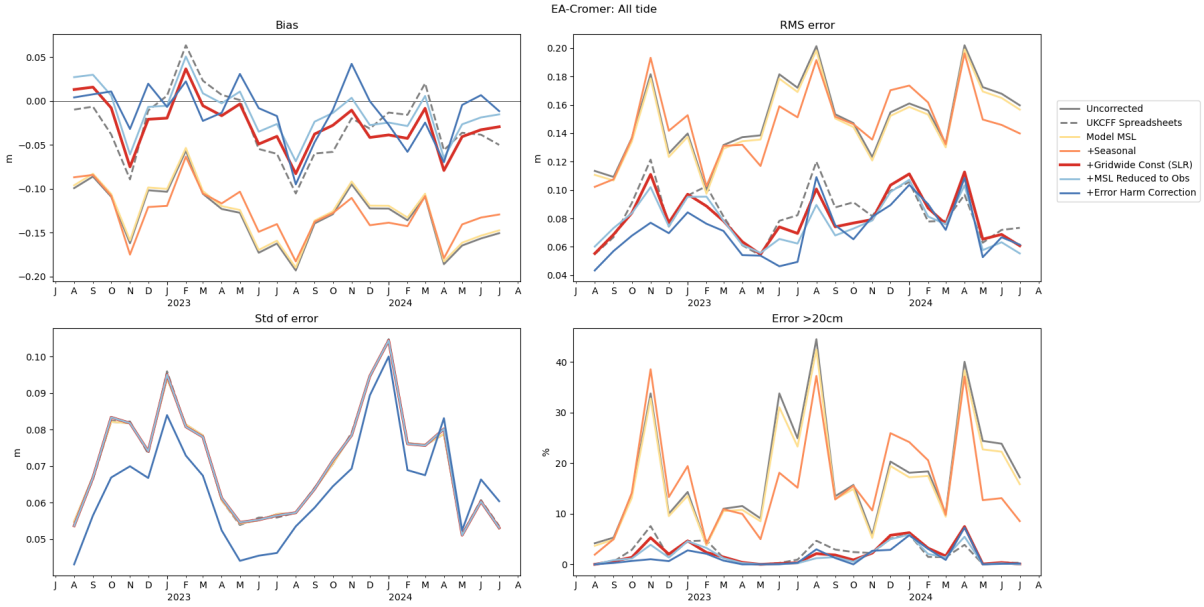

Figure A.5: All tide statistics for site EA-Cromer from August 2022–July 2024

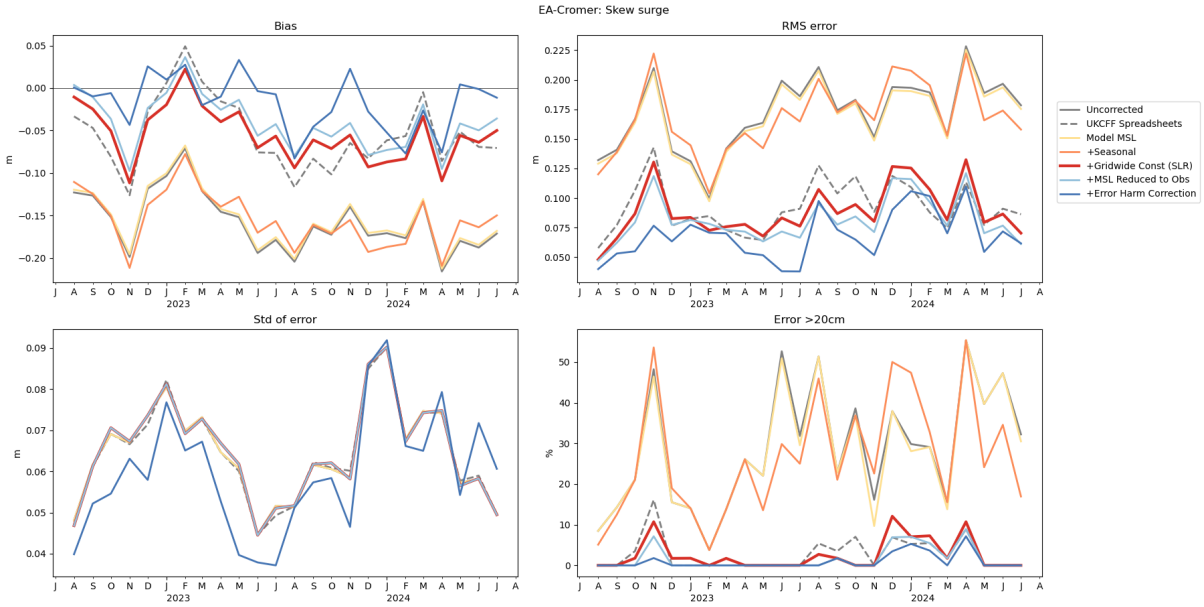

Figure A.6: Skew surge statistics for site EA-Cromer from August 2022–July 2024

© Crown Copyright 2025, Met Office

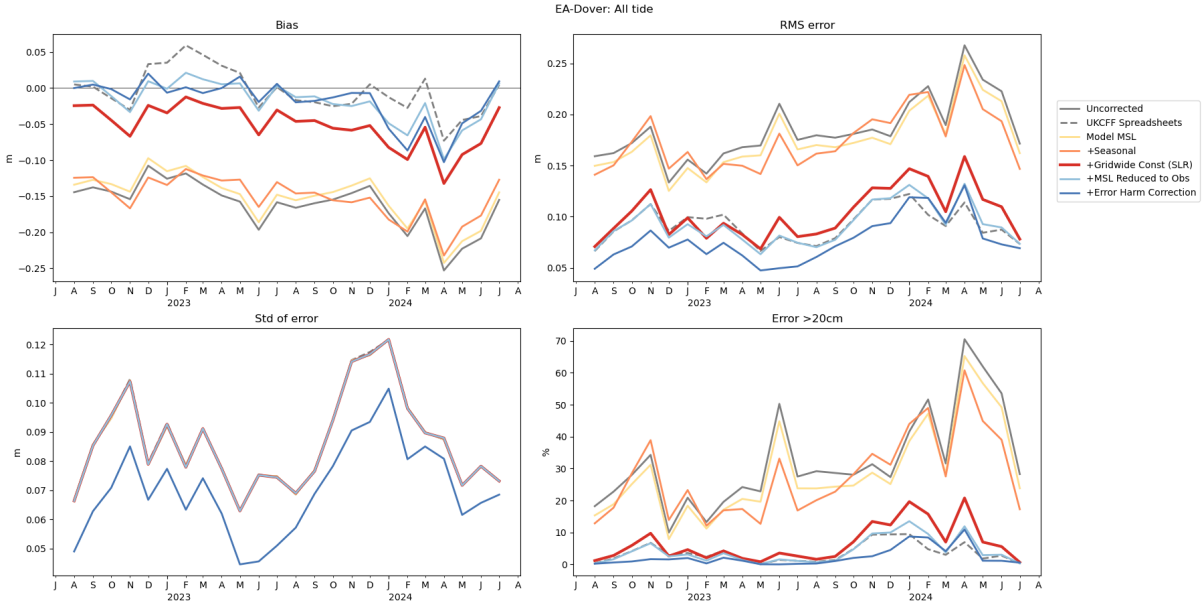

Figure A.7: All tide statistics for site EA-Dover from August 2022–July 2024

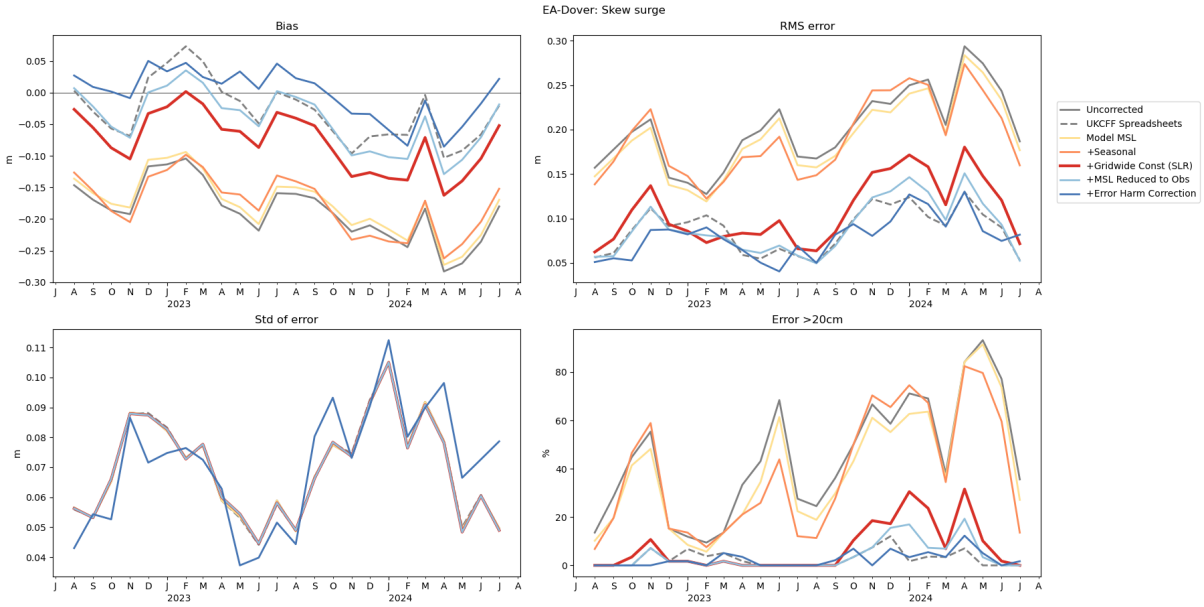

Figure A.8: Skew surge statistics for site EA-Dover from August 2022–July 2024

© Crown Copyright 2025, Met Office

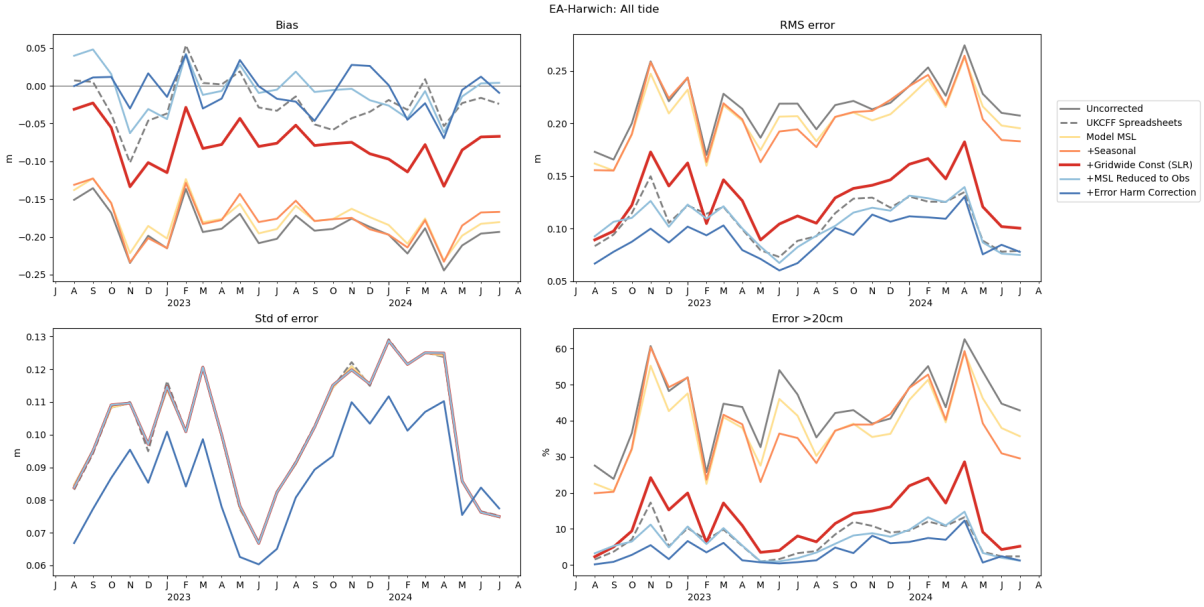

Figure A.9: All tide statistics for site EA-Harwich from August 2022–July 2024

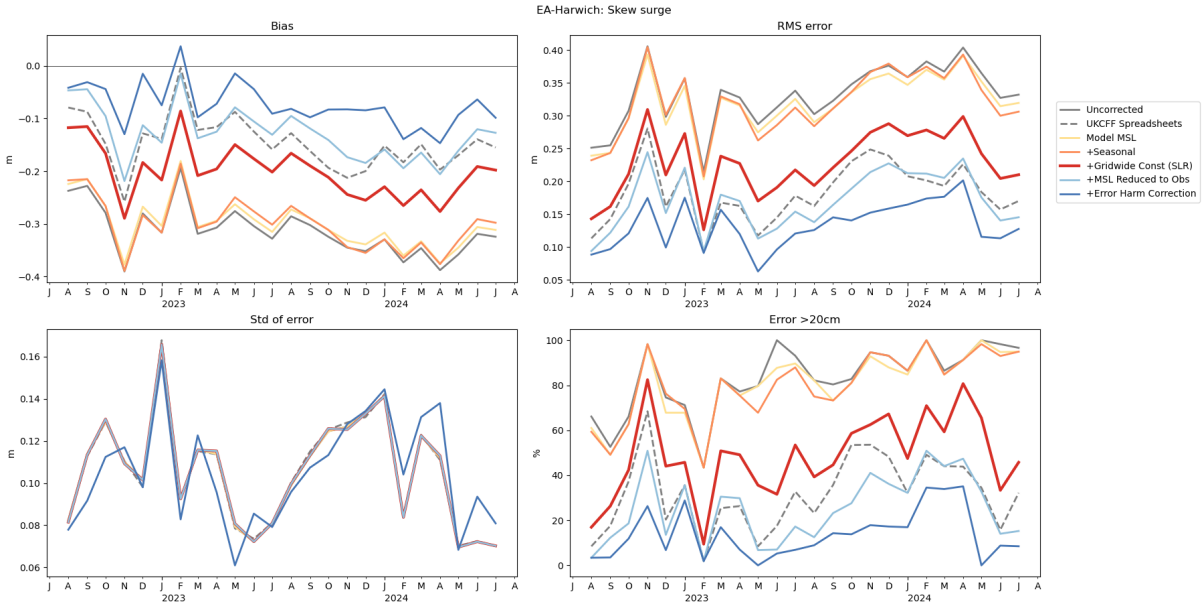

Figure A.10: Skew surge statistics for site EA-Harwich from August 2022–July 2024

© Crown Copyright 2025, Met Office

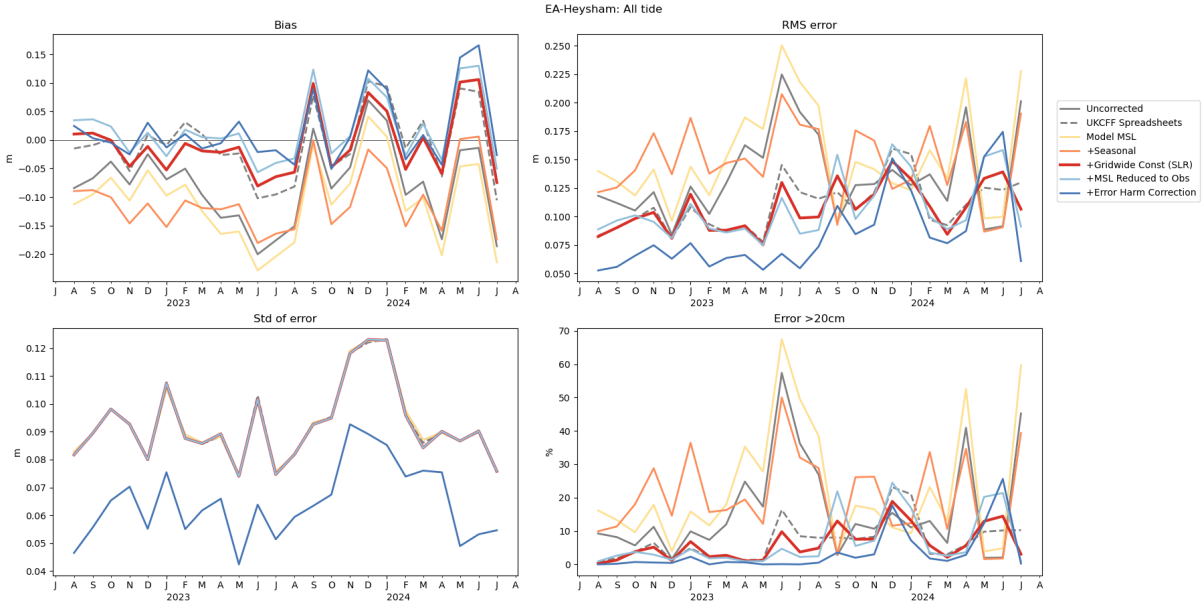

Figure A.11: All tide statistics for site EA-Heysham from August 2022–July 2024

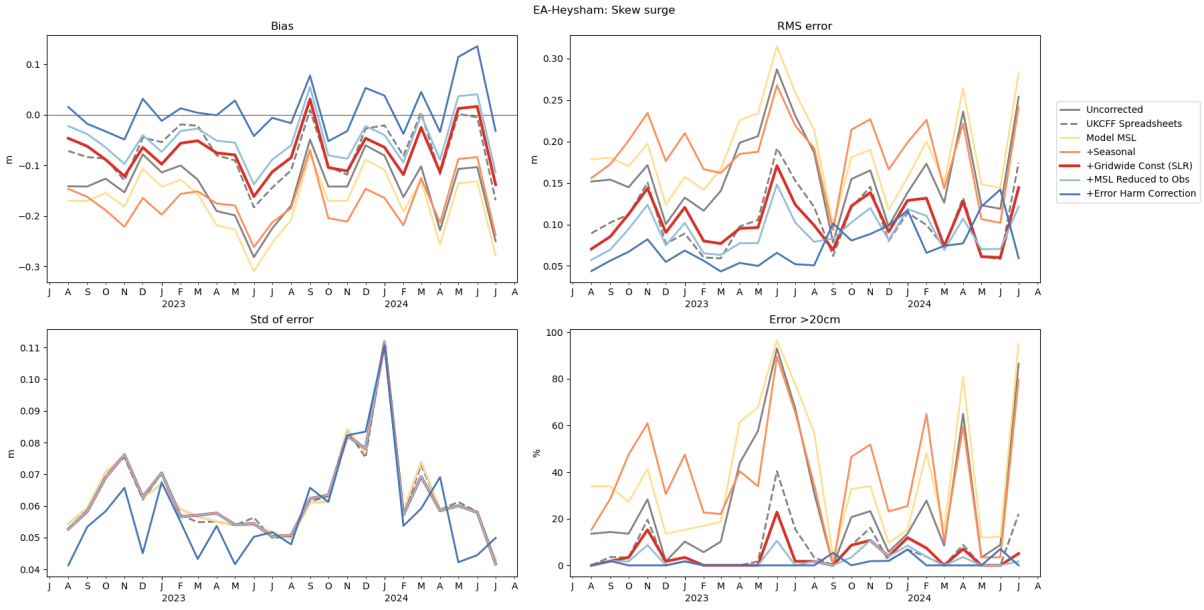

Figure A.12: Skew surge statistics for site EA-Heysham from August 2022–July 2024

© Crown Copyright 2025, Met Office

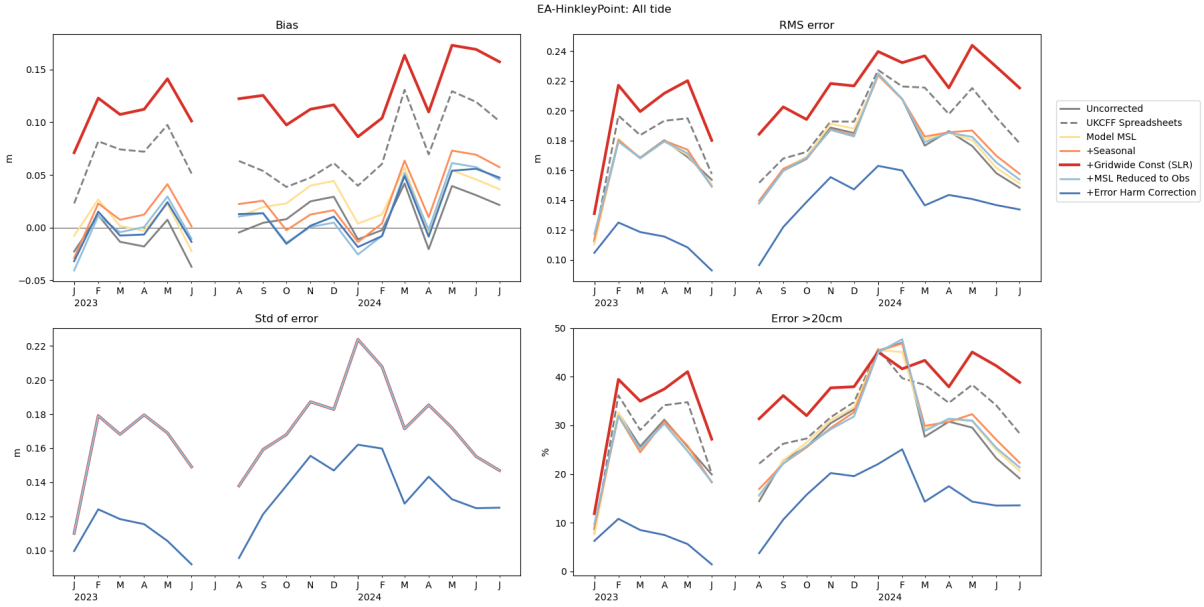

Figure A.13: All tide statistics for site EA-HinkleyPoint from August 2022–July 2024

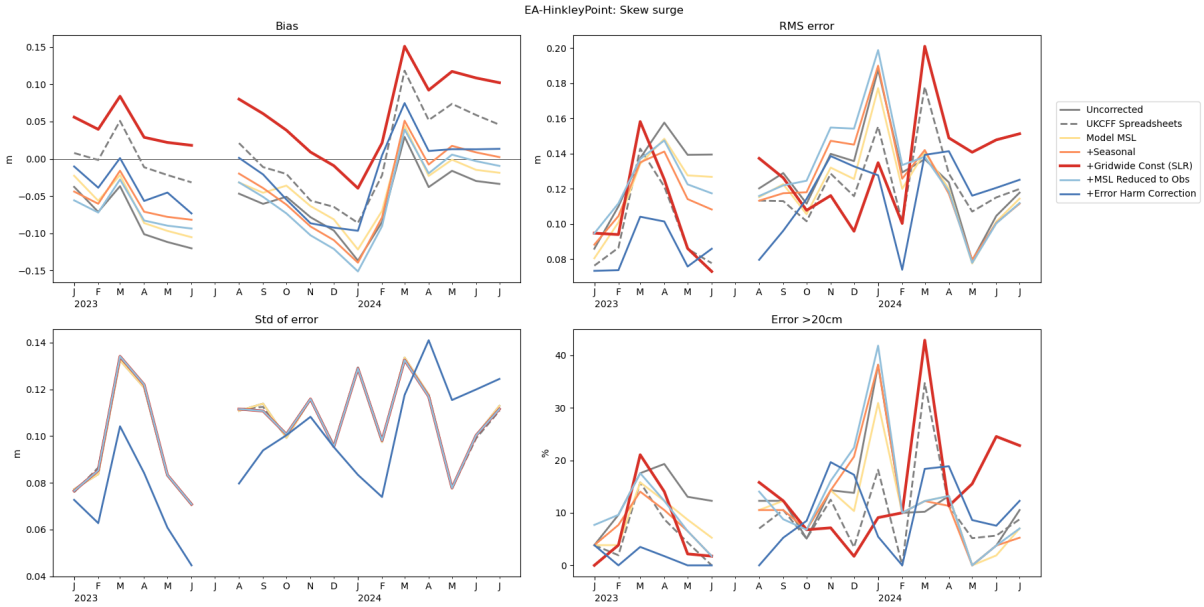

Figure A.14: Skew surge statistics for site EA-HinkleyPoint from August 2022–July 2024

© Crown Copyright 2025, Met Office

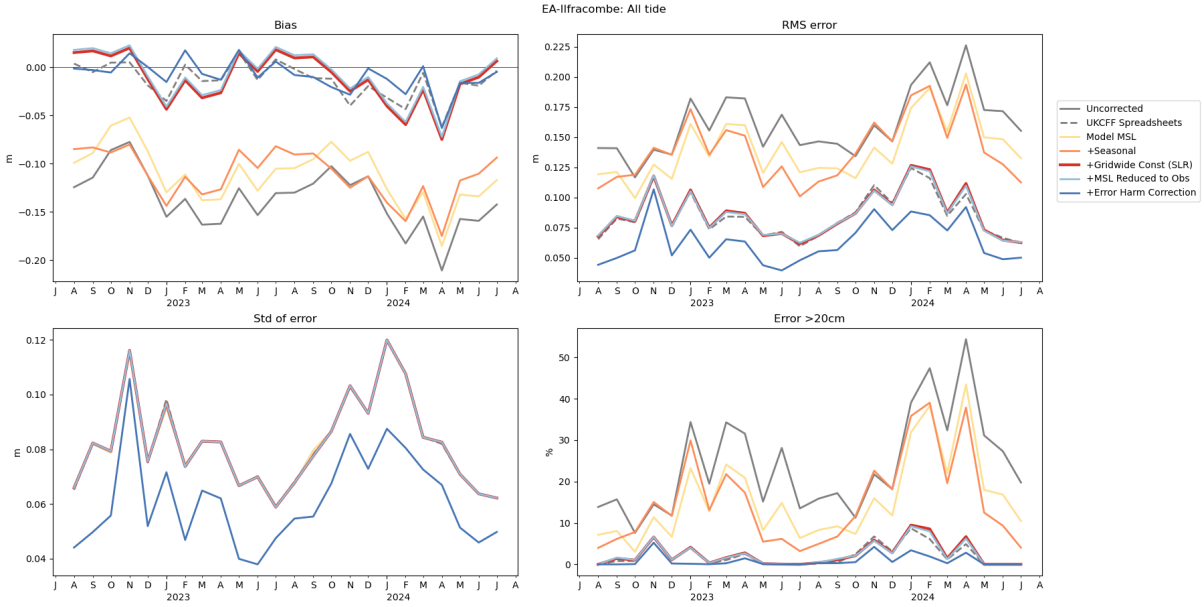

Figure A.15: All tide statistics for site EA-Ilfracombe from August 2022–July 2024

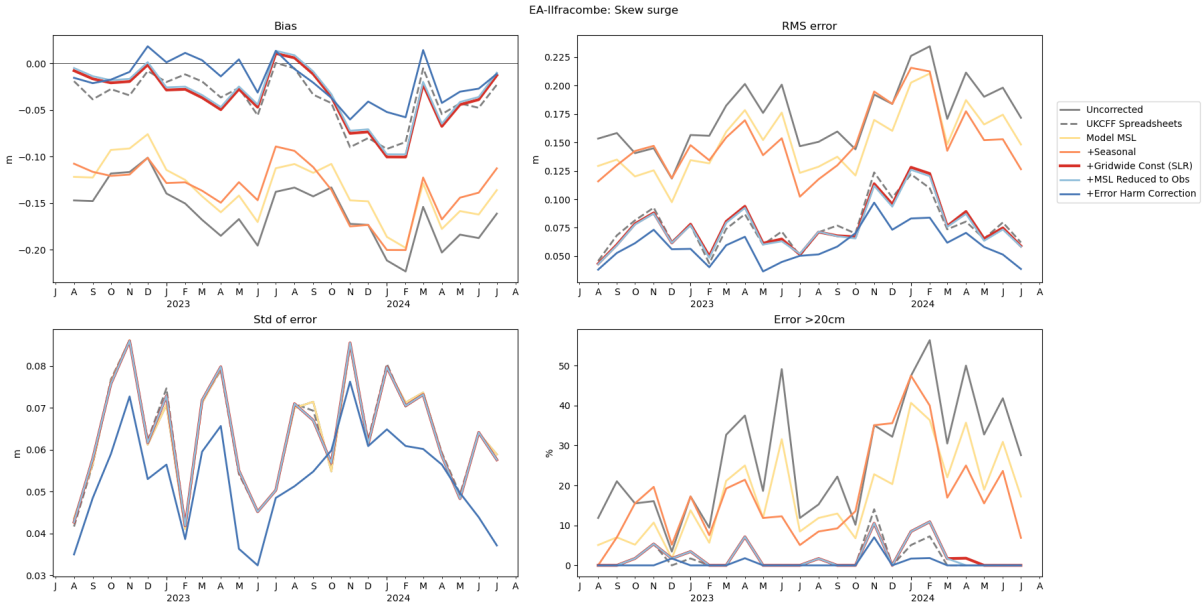

Figure A.16: Skew surge statistics for site EA-Ilfracombe from August 2022–July 2024

© Crown Copyright 2025, Met Office

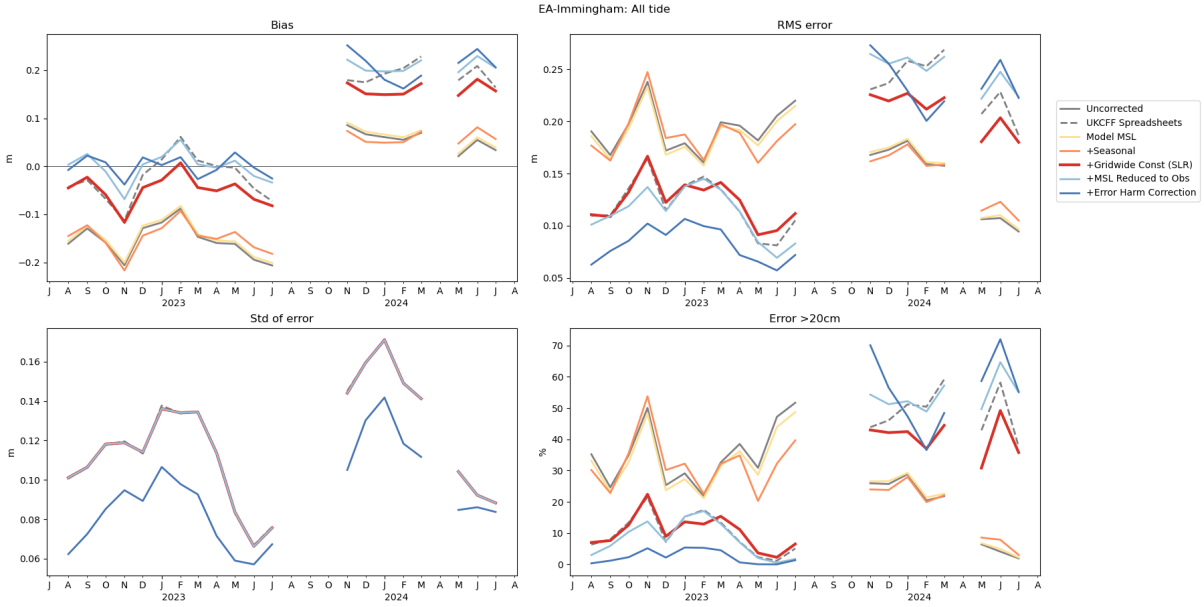

Figure A.17: All tide statistics for site EA-Immingham from August 2022–July 2024

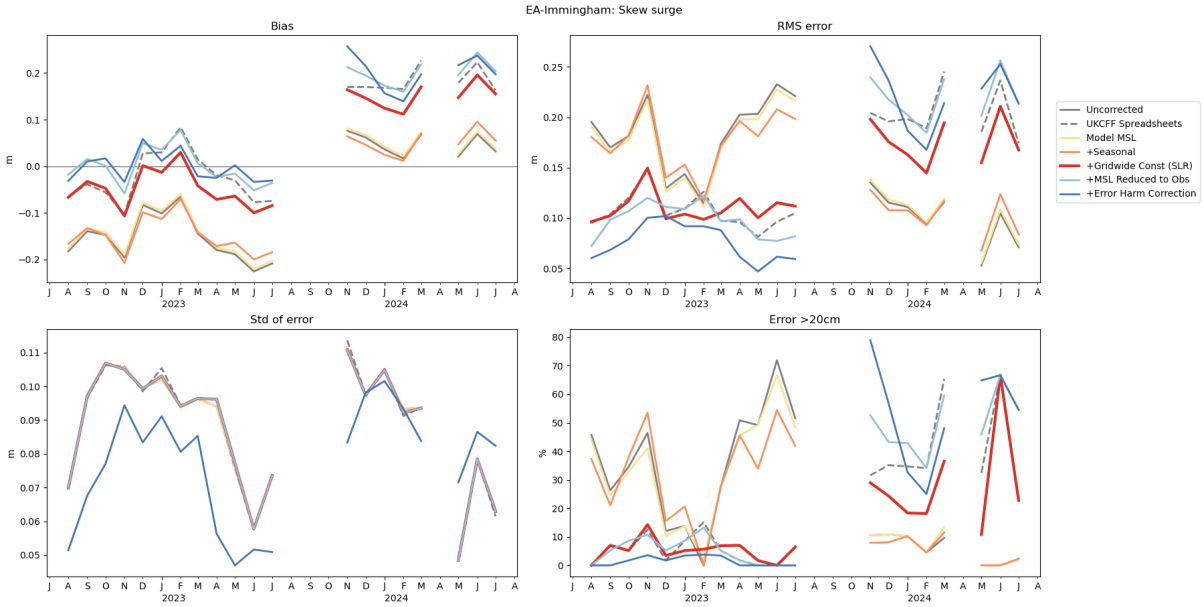

Figure A.18: Skew surge statistics for site EA-Immingham from August 2022–July 2024

© Crown Copyright 2025, Met Office

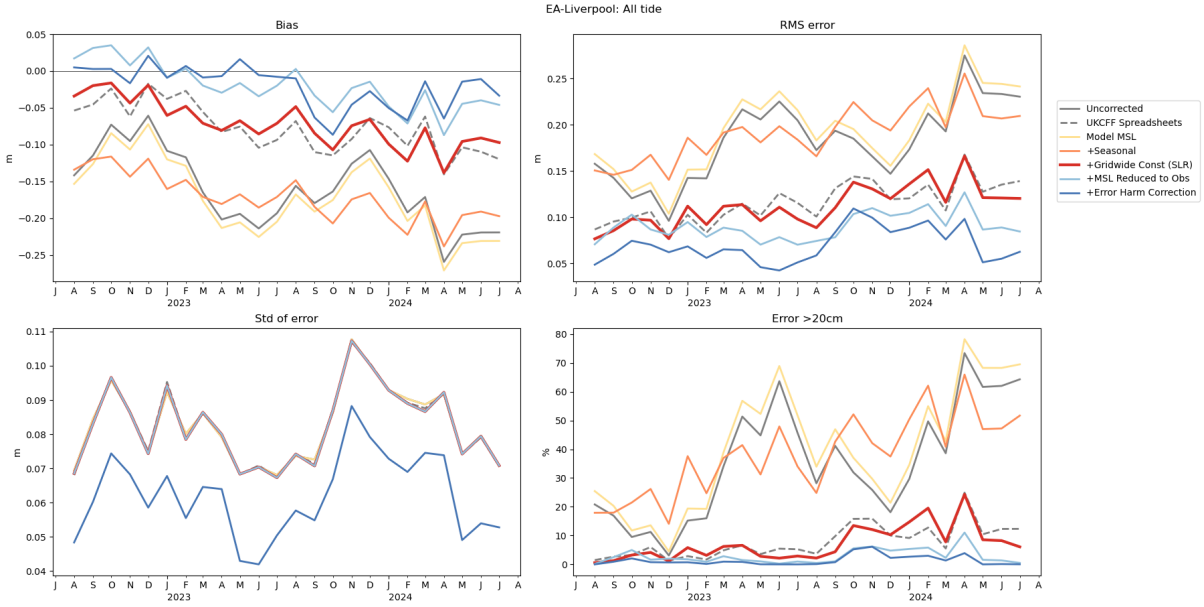

Figure A.19: All tide statistics for site EA-Liverpool from August 2022–July 2024

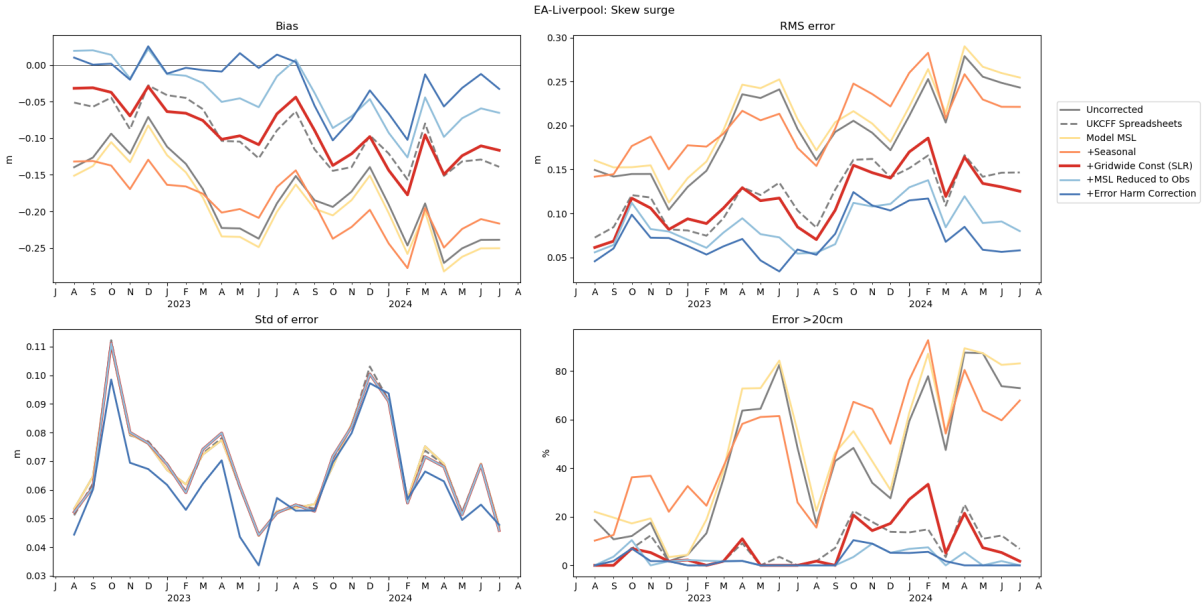

Figure A.20: Skew surge statistics for site EA-Liverpool from August 2022–July 2024

© Crown Copyright 2025, Met Office

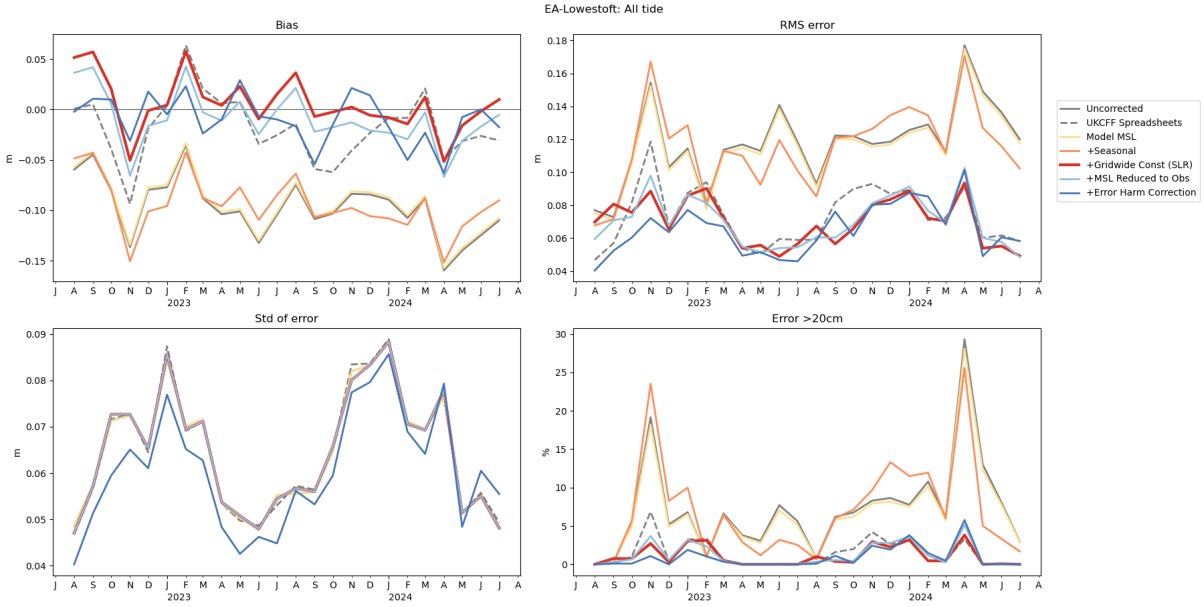

Figure A.21: All tide statistics for site EA-Lowestoft from August 2022–July 2024

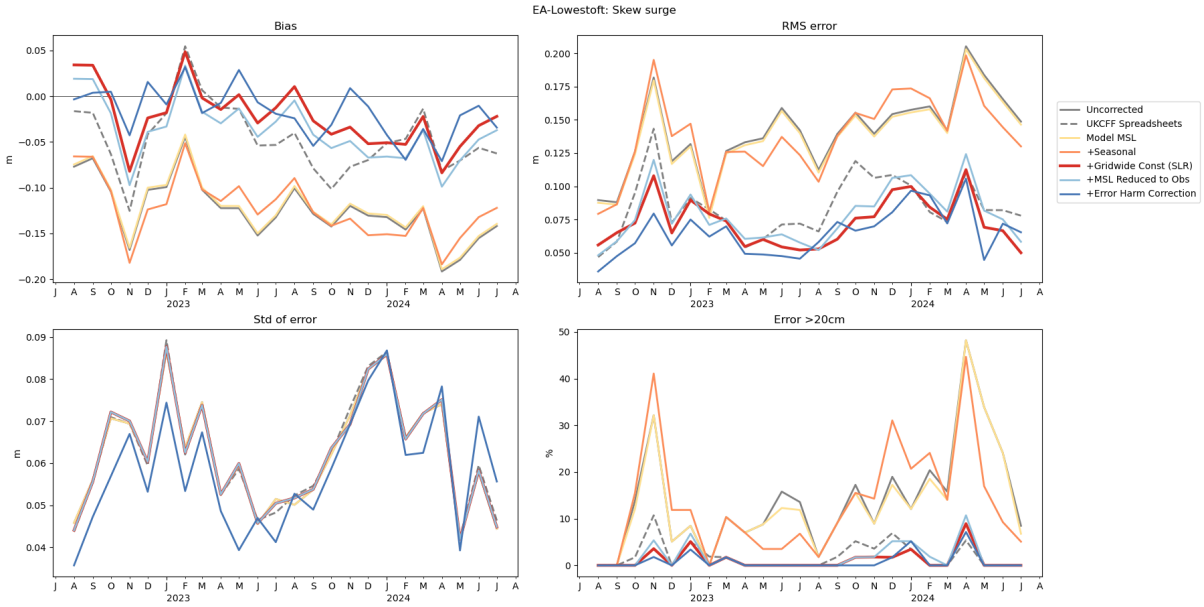

Figure A.22: Skew surge statistics for site EA-Lowestoft from August 2022–July 2024

© Crown Copyright 2025, Met Office

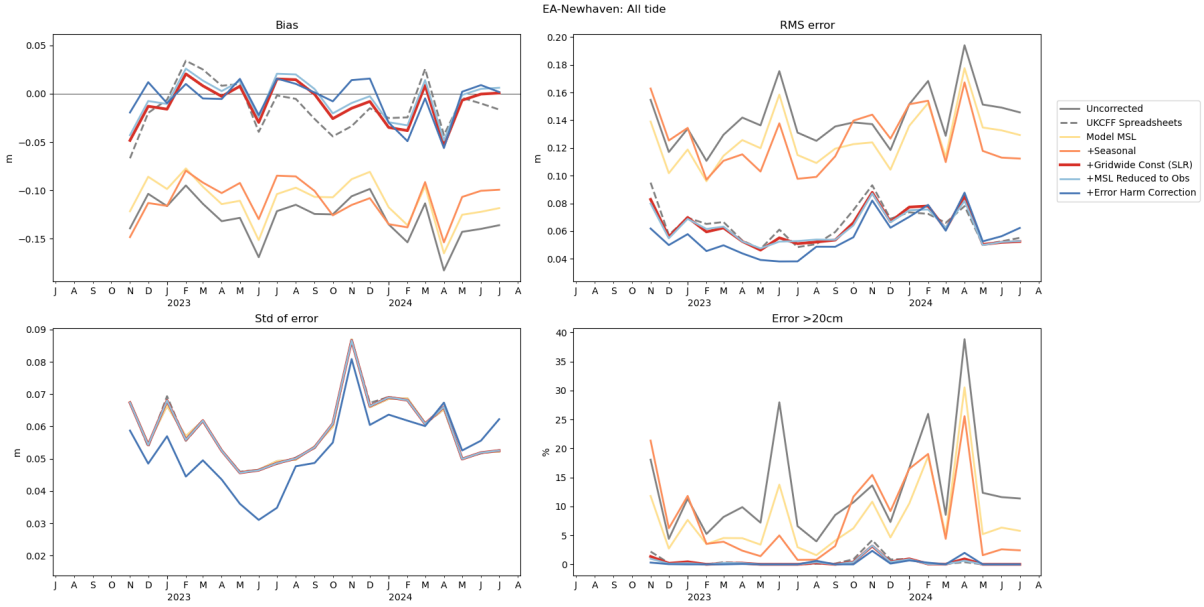

Figure A.23: All tide statistics for site EA-Newhaven from August 2022–July 2024

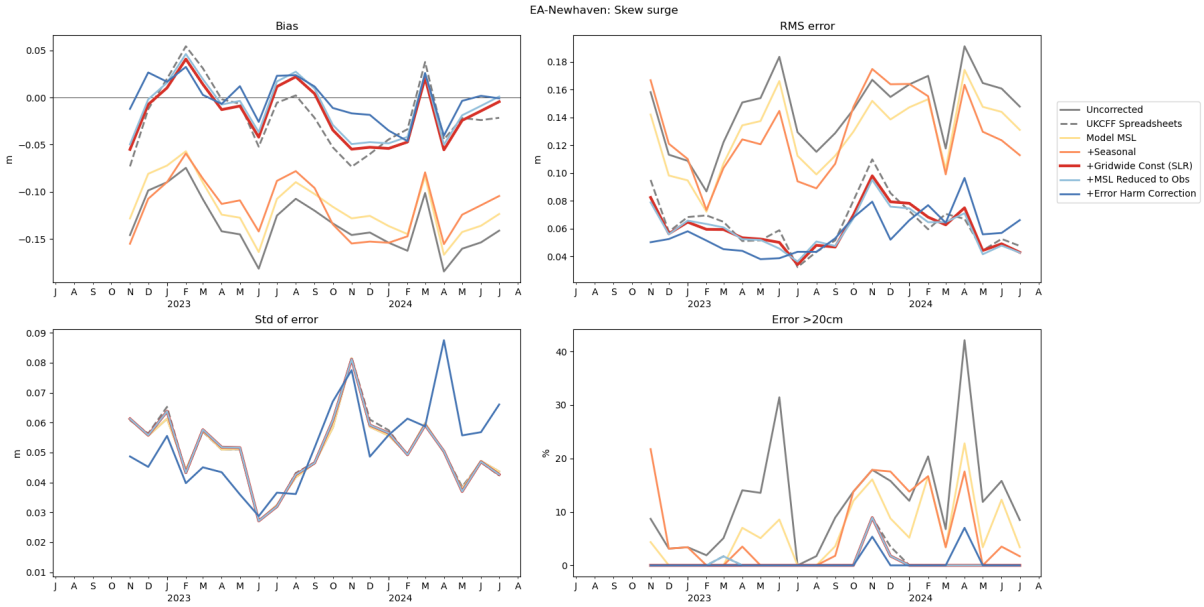

Figure A.24: Skew surge statistics for site EA-Newhaven from August 2022–July 2024

© Crown Copyright 2025, Met Office

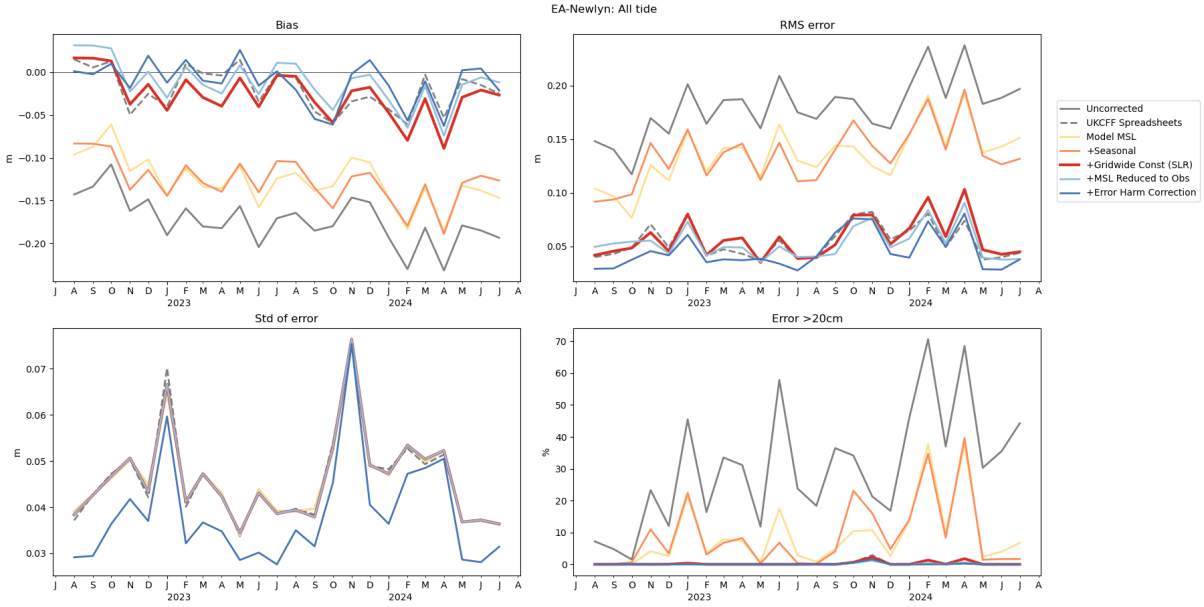

Figure A.25: All tide statistics for site EA-Newlyn from August 2022–July 2024

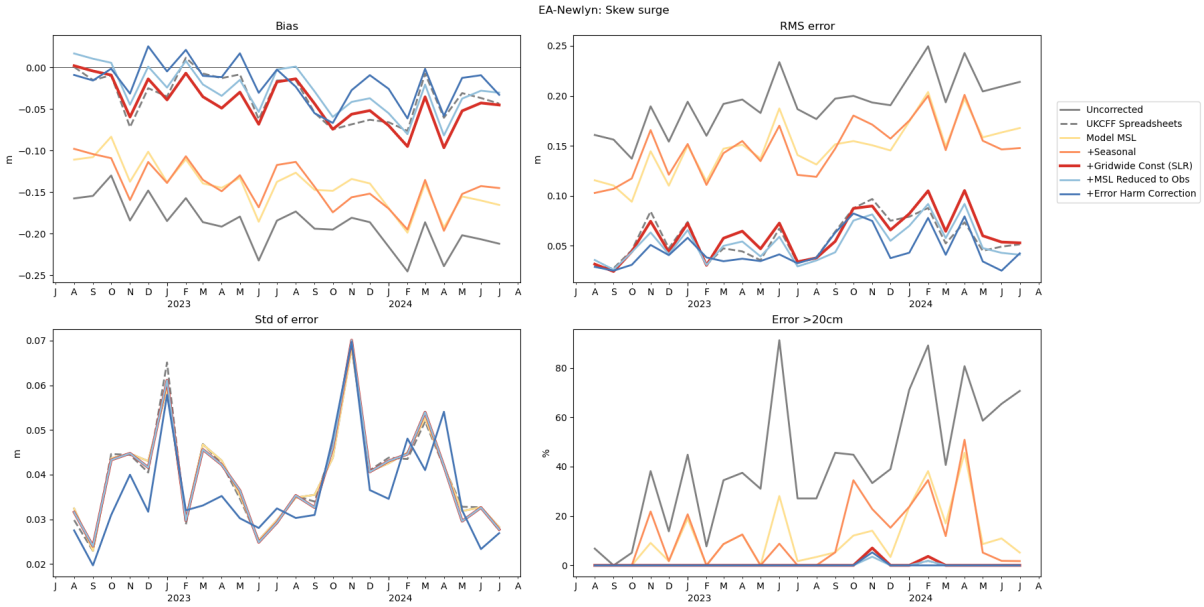

Figure A.26: Skew surge statistics for site EA-Newlyn from August 2022–July 2024

© Crown Copyright 2025, Met Office

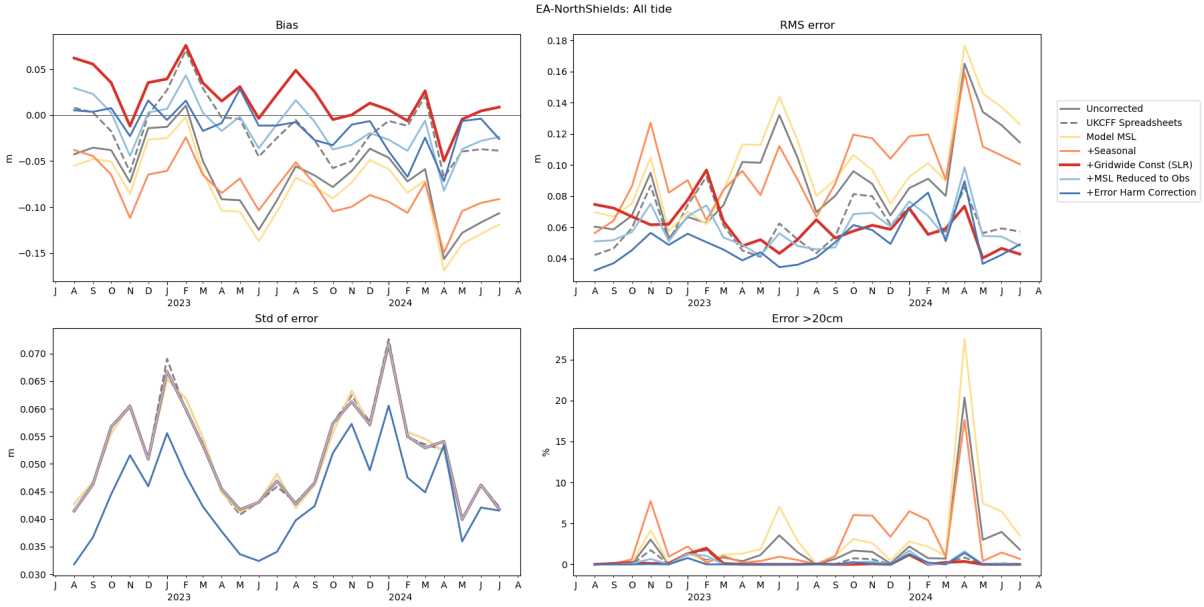

Figure A.27: All tide statistics for site EA-NorthShields from August 2022–July 2024

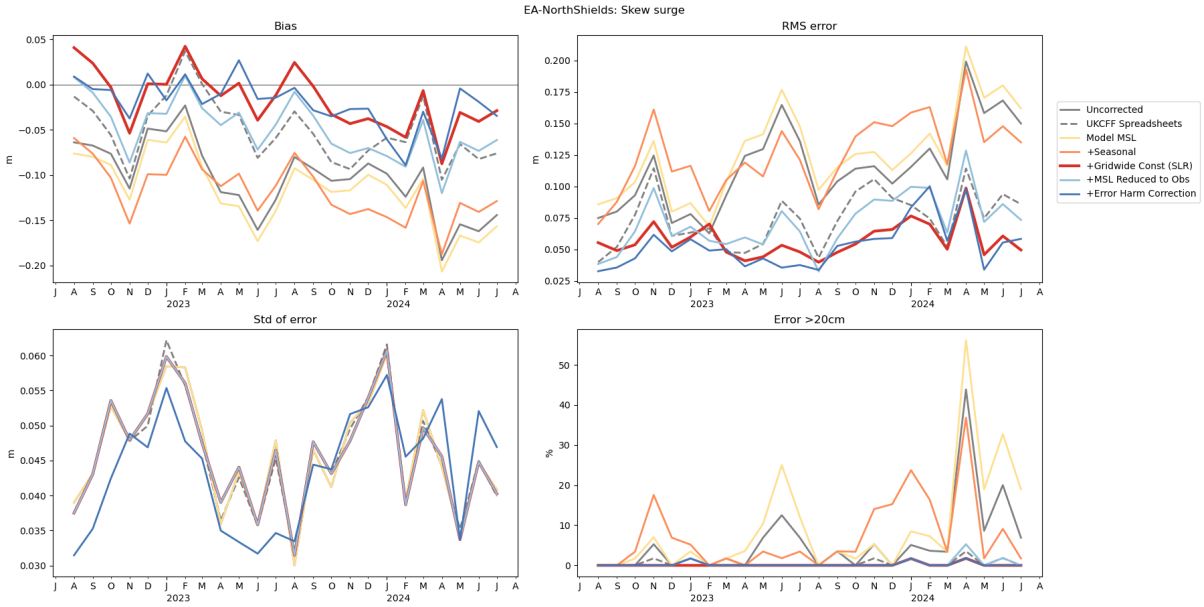

Figure A.28: Skew surge statistics for site EA-NorthShields from August 2022–July 2024

© Crown Copyright 2025, Met Office

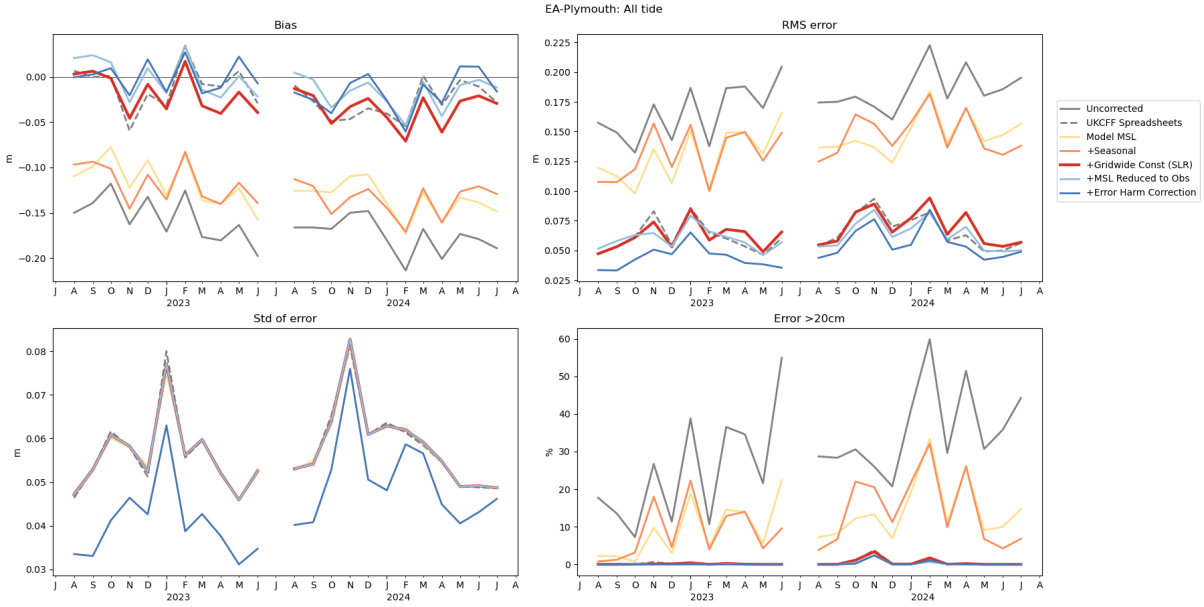

Figure A.29: All tide statistics for site EA-Plymouth from August 2022–July 2024

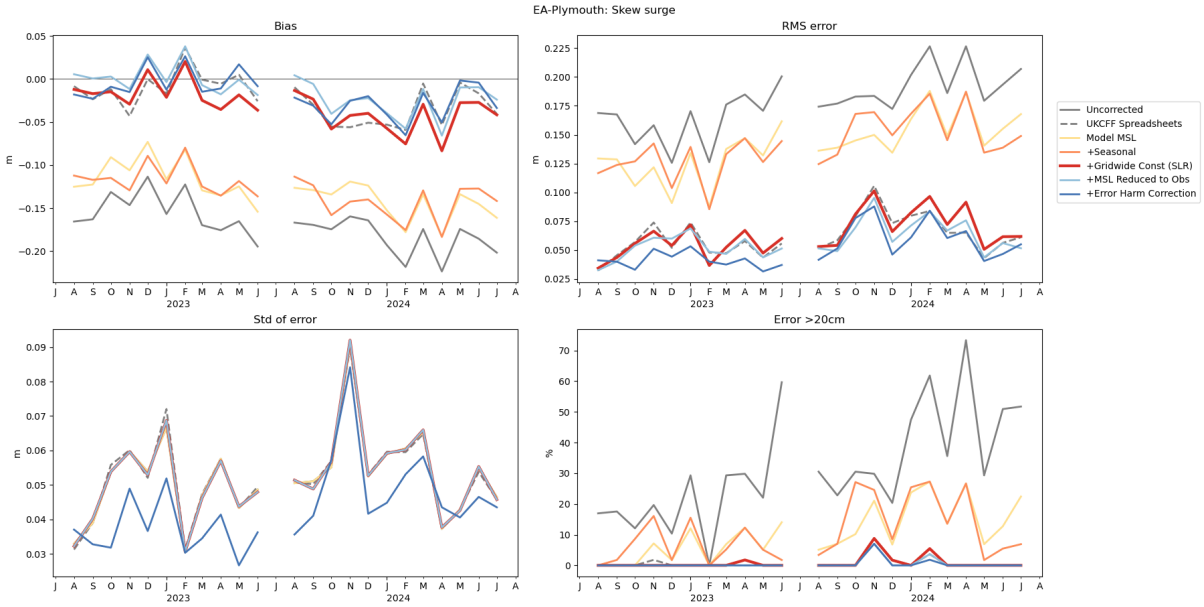

Figure A.30: Skew surge statistics for site EA-Plymouth from August 2022–July 2024

© Crown Copyright 2025, Met Office

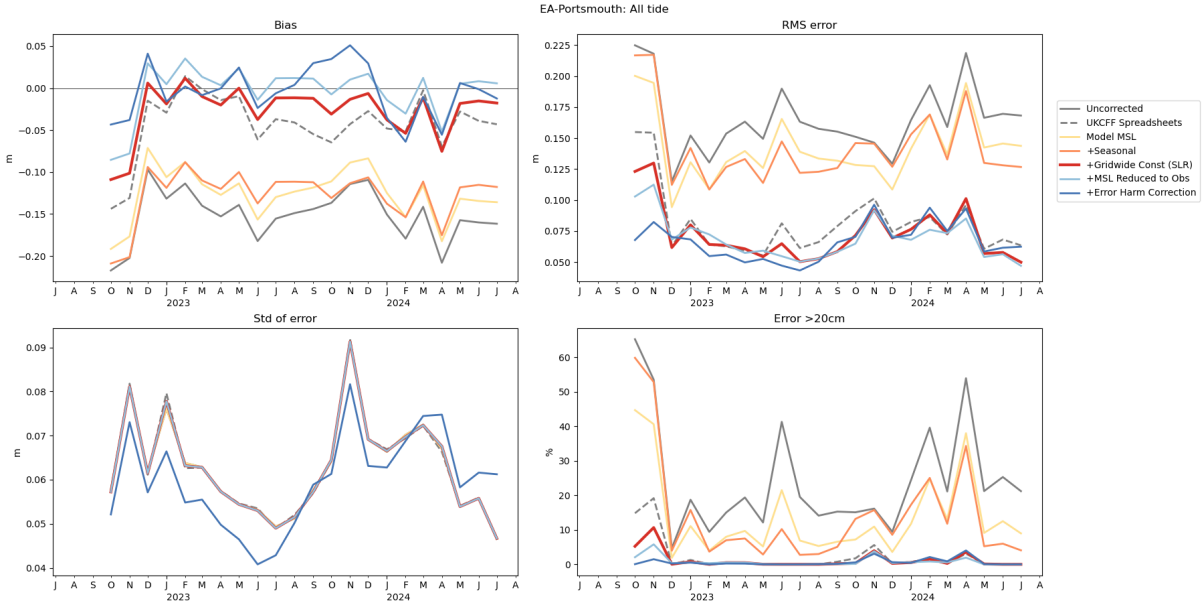

Figure A.31: All tide statistics for site EA-Portsmouth from August 2022–July 2024

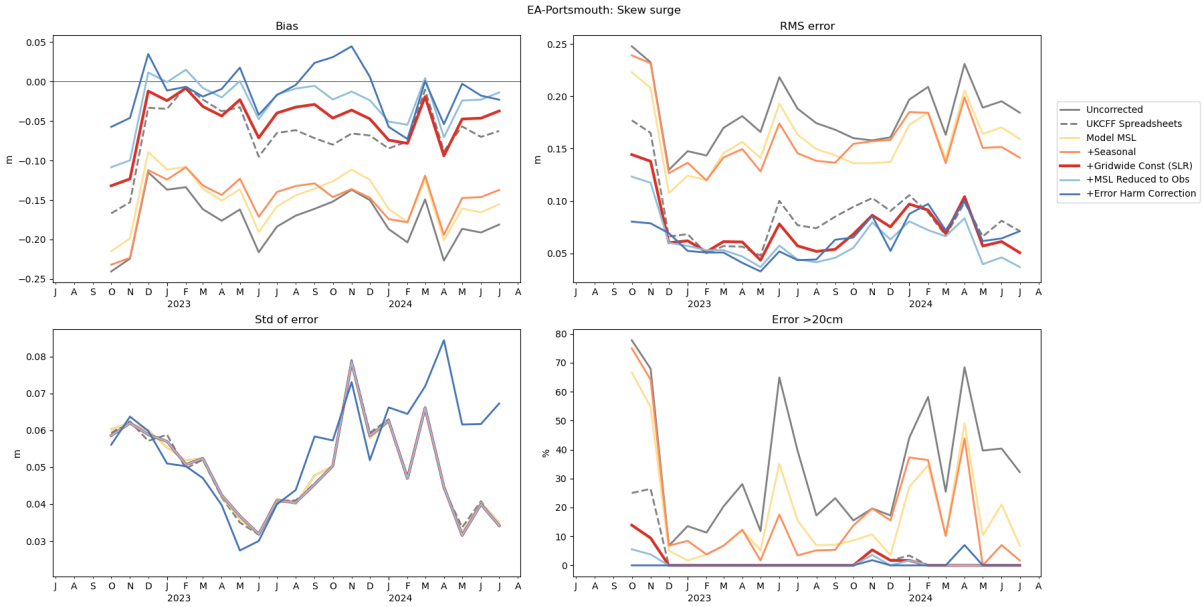

Figure A.32: Skew surge statistics for site EA-Portsmouth from August 2022–July 2024

© Crown Copyright 2025, Met Office

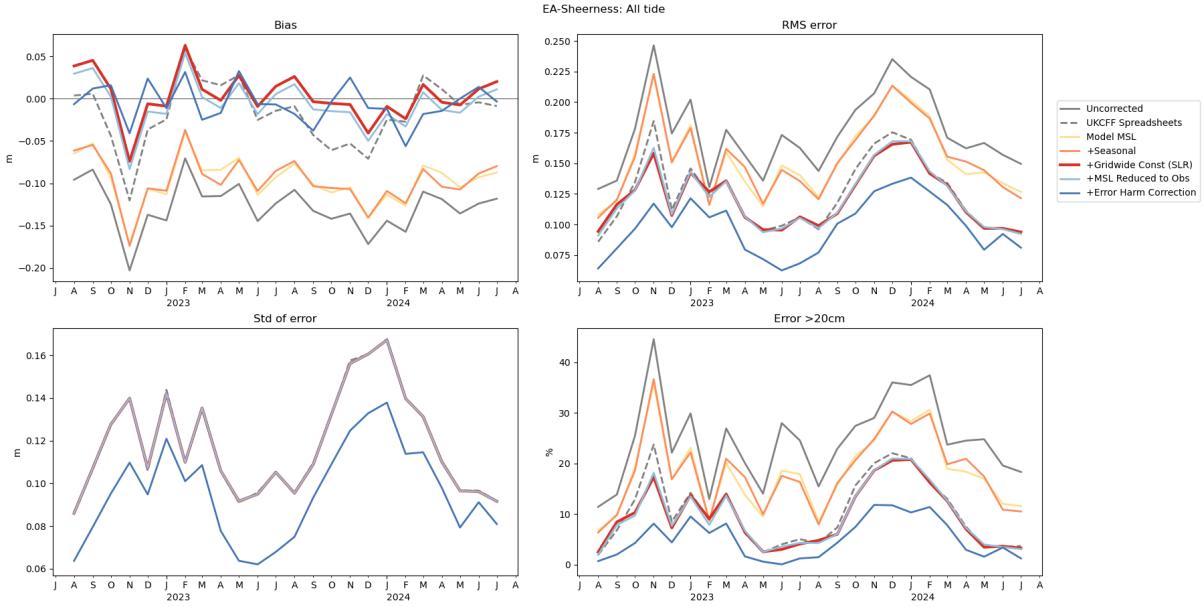

Figure A.33: All tide statistics for site EA-Sheerness from August 2022–July 2024

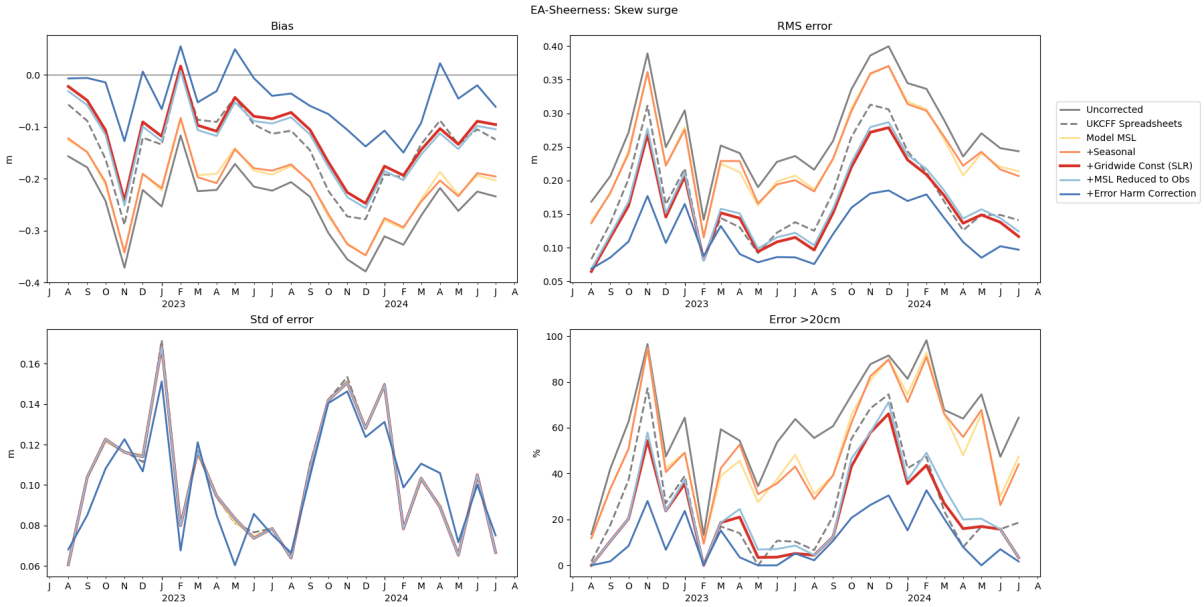

Figure A.34: Skew surge statistics for site EA-Sheerness from August 2022–July 2024

© Crown Copyright 2025, Met Office

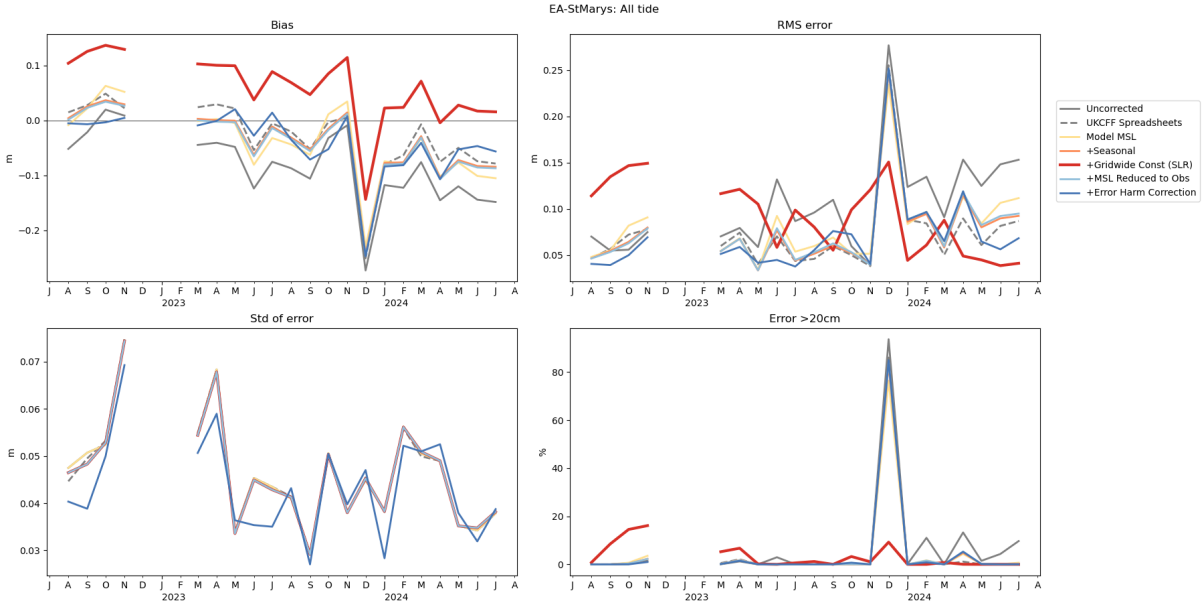

Figure A.35: All tide statistics for site EA-StMarys from August 2022–July 2024

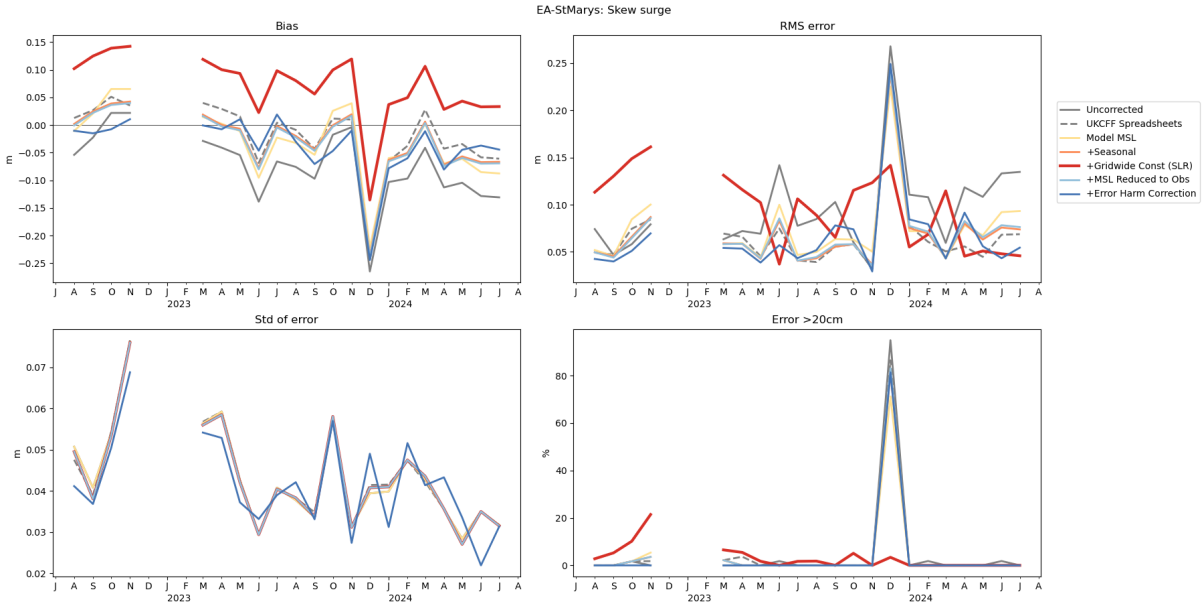

Figure A.36: Skew surge statistics for site EA-StMarys from August 2022–July 2024

© Crown Copyright 2025, Met Office

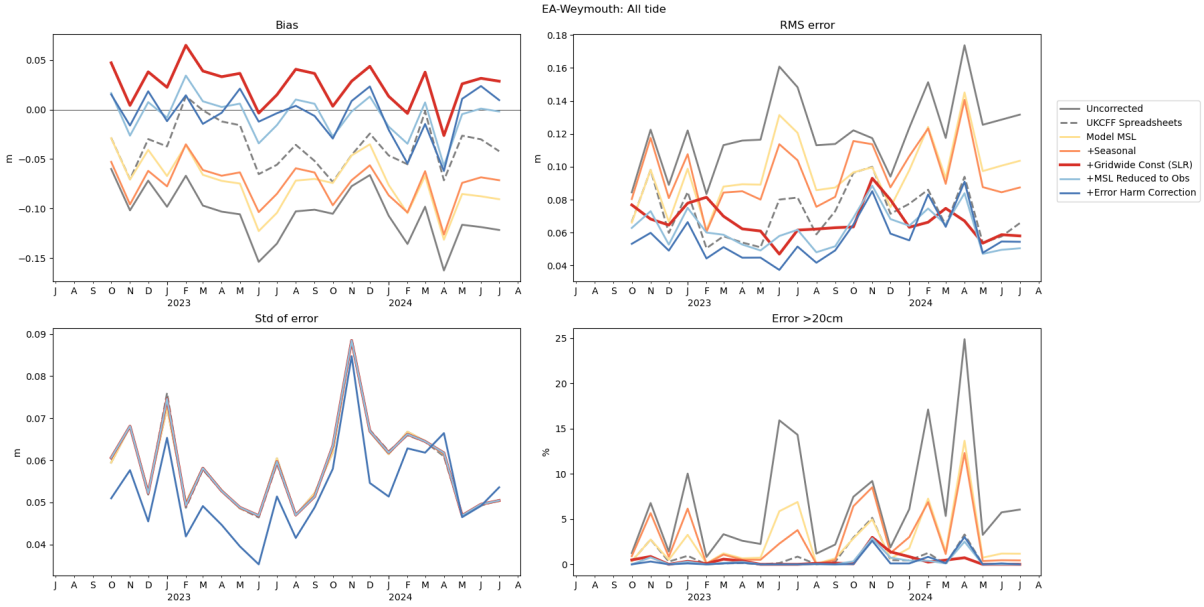

Figure A.37: All tide statistics for site EA-Weymouth from August 2022–July 2024

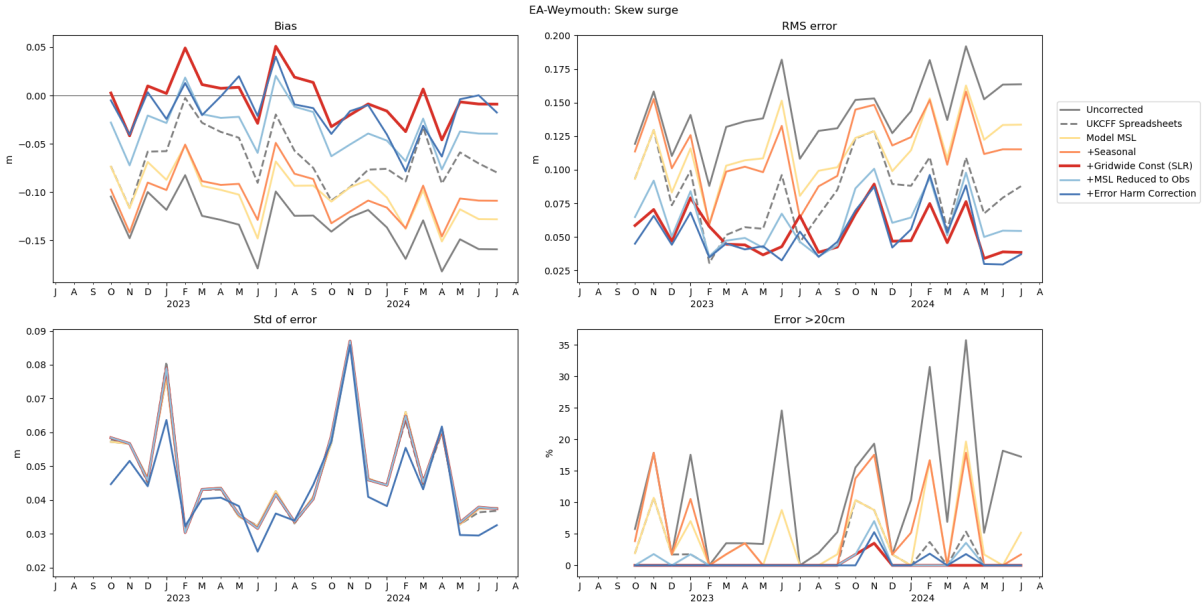

Figure A.38: Skew surge statistics for site EA-Weymouth from August 2022–July 2024

© Crown Copyright 2025, Met Office

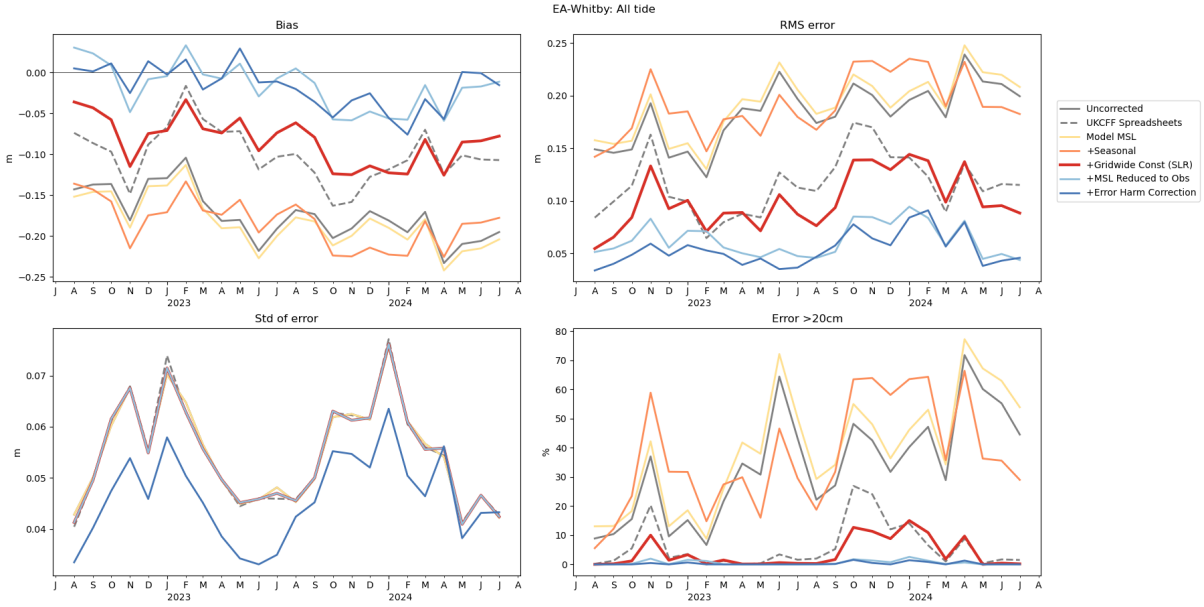

Figure A.39: All tide statistics for site EA-Whitby from August 2022–July 2024

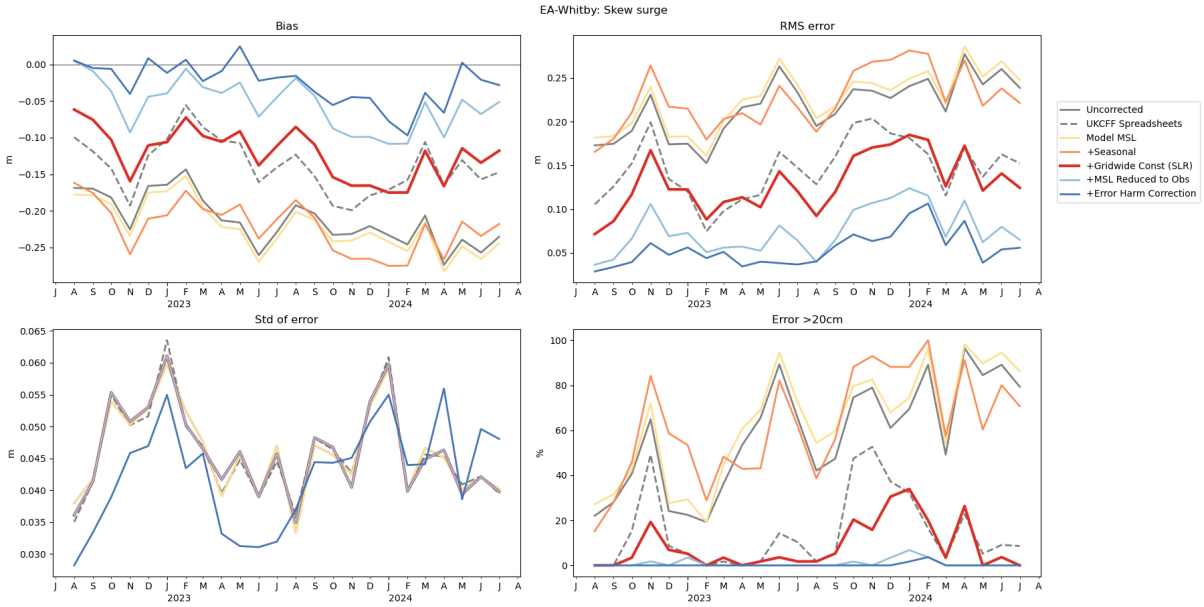

Figure A.40: Skew surge statistics for site EA-Whitby from August 2022–July 2024

© Crown Copyright 2025, Met Office

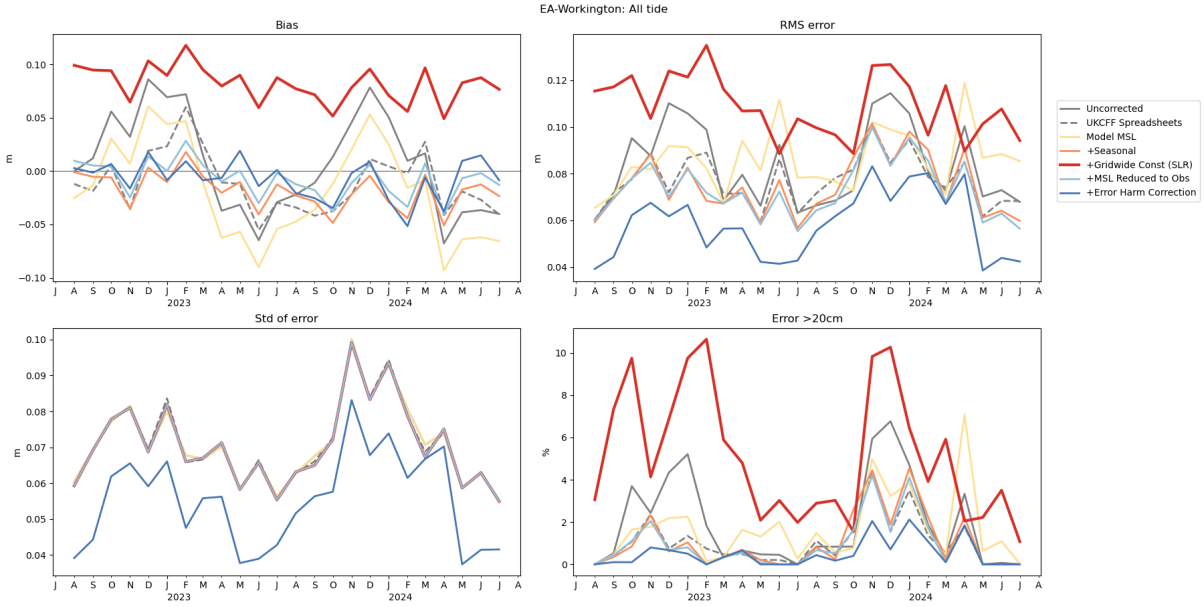

Figure A.41: All tide statistics for site EA-Workington from August 2022–July 2024

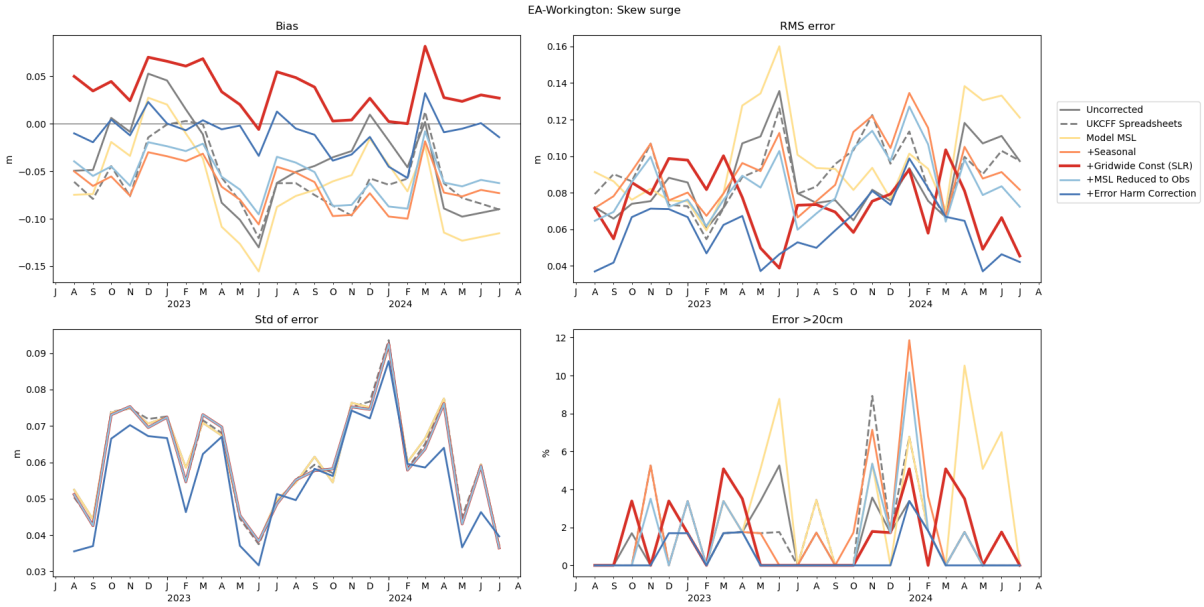

Figure A.42: Skew surge statistics for site EA-Workington from August 2022–July 2024

© Crown Copyright 2025, Met Office

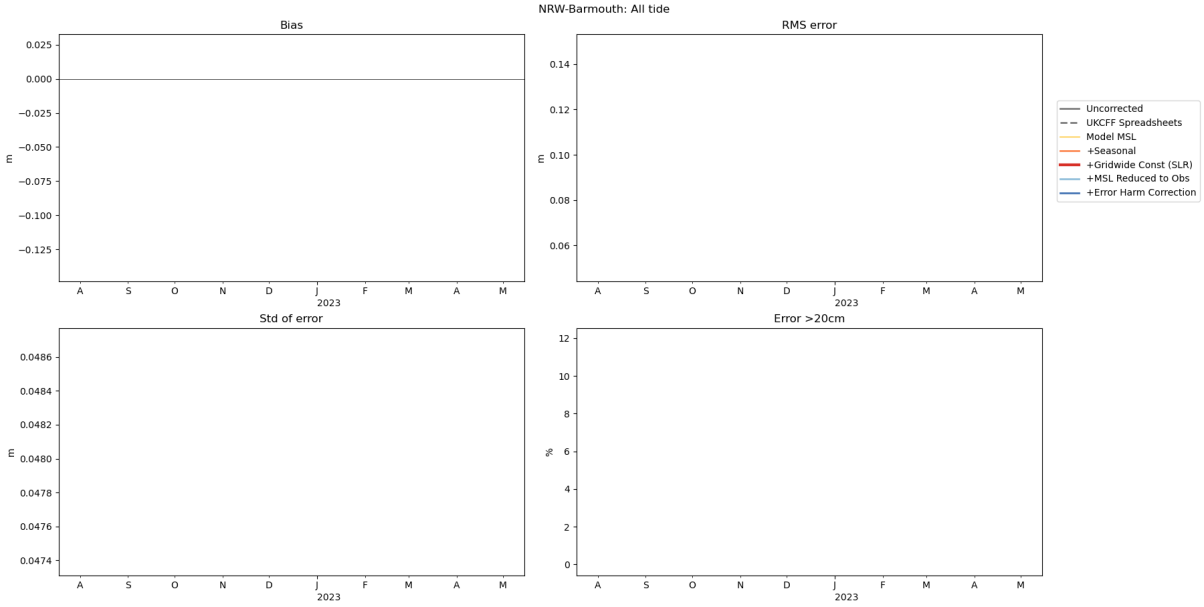

Figure A.43: All tide statistics for site NRW-Barmouth from August 2022–July 2024

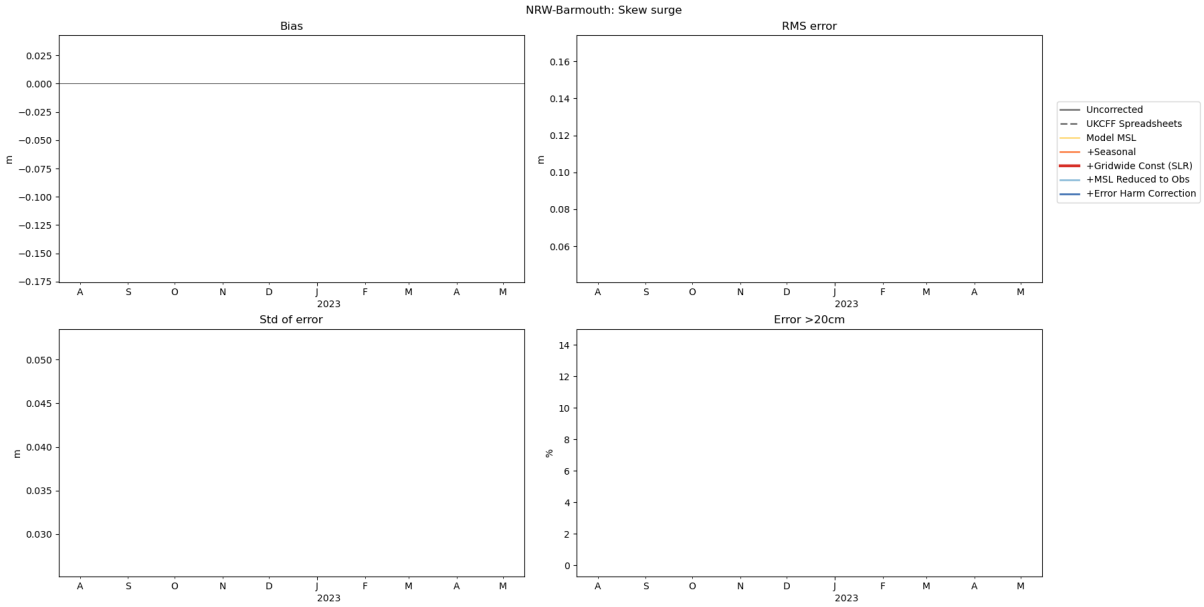

Figure A.44: Skew surge statistics for site NRW-Barmouth from August 2022–July 2024

© Crown Copyright 2025, Met Office

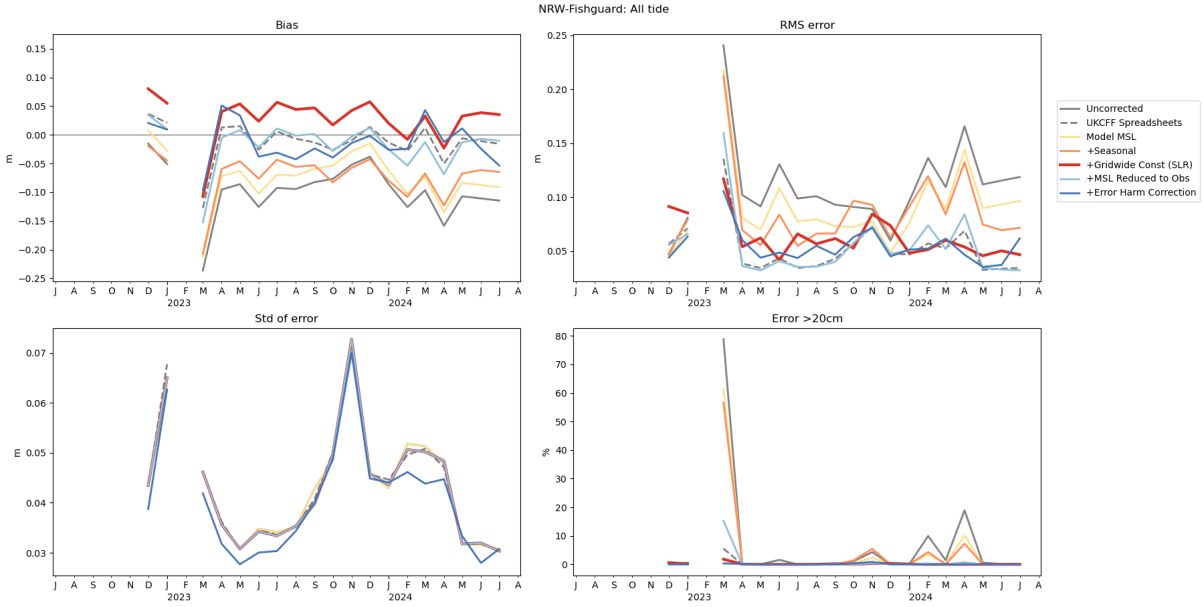

Figure A.45: All tide statistics for site NRW-Fishguard from August 2022–July 2024

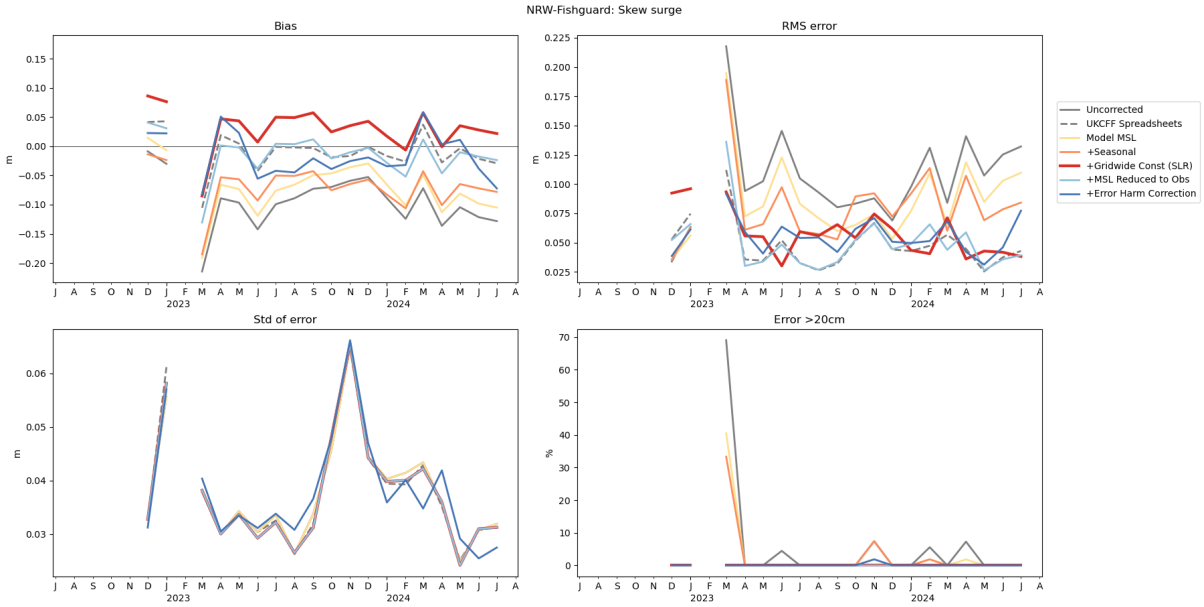

Figure A.46: Skew surge statistics for site NRW-Fishguard from August 2022–July 2024

© Crown Copyright 2025, Met Office

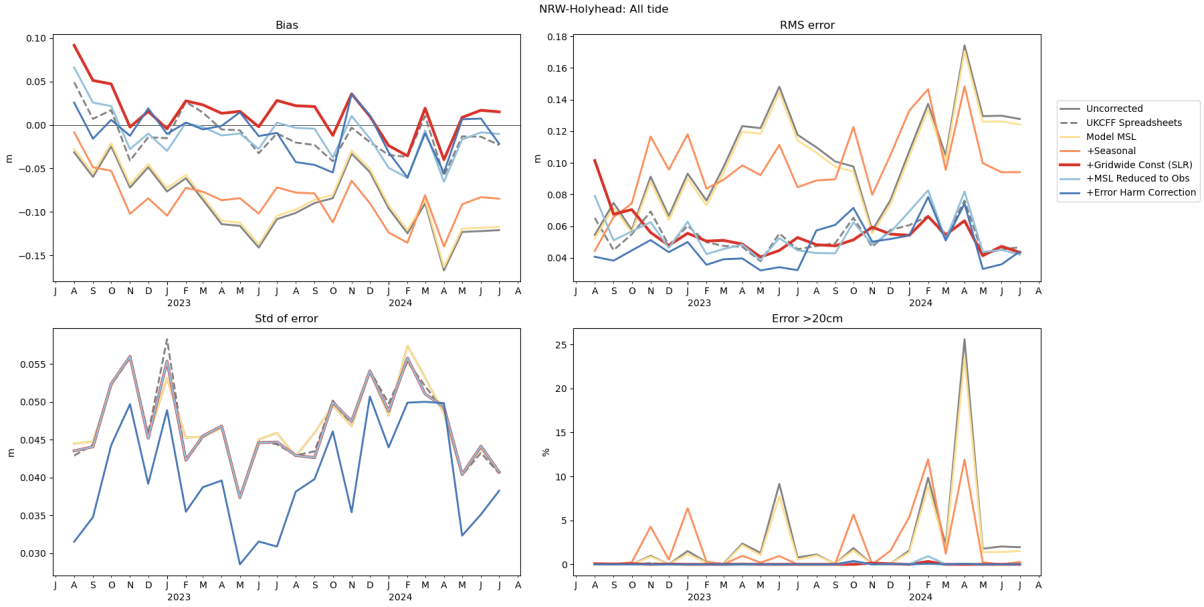

Figure A.47: All tide statistics for site NRW-Holyhead from August 2022–July 2024

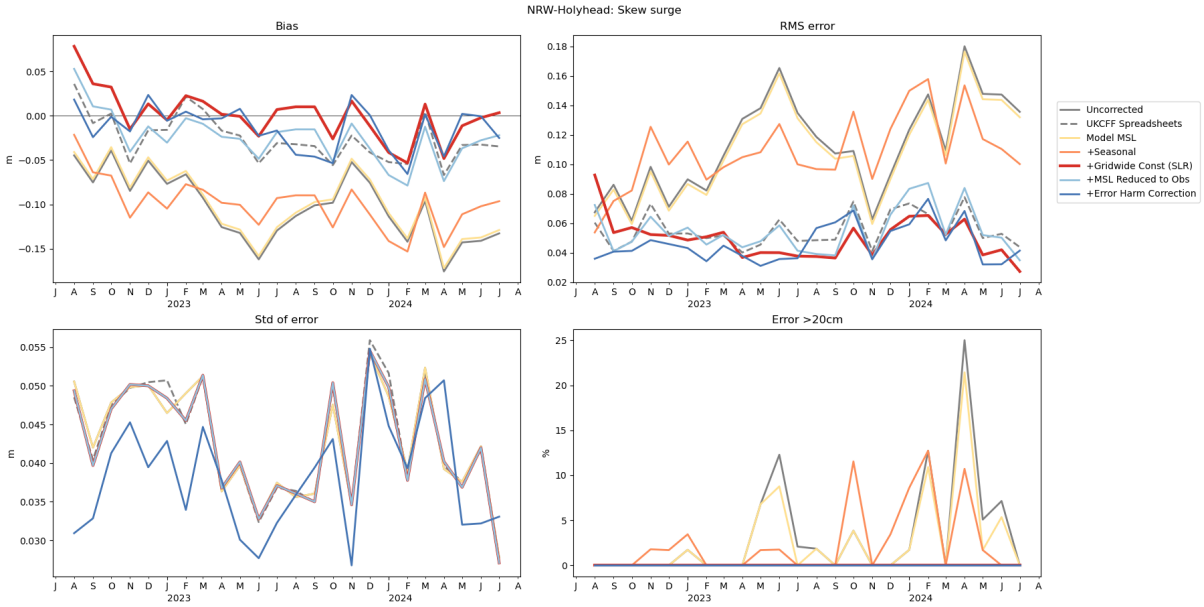

Figure A.48: Skew surge statistics for site NRW-Holyhead from August 2022–July 2024

© Crown Copyright 2025, Met Office

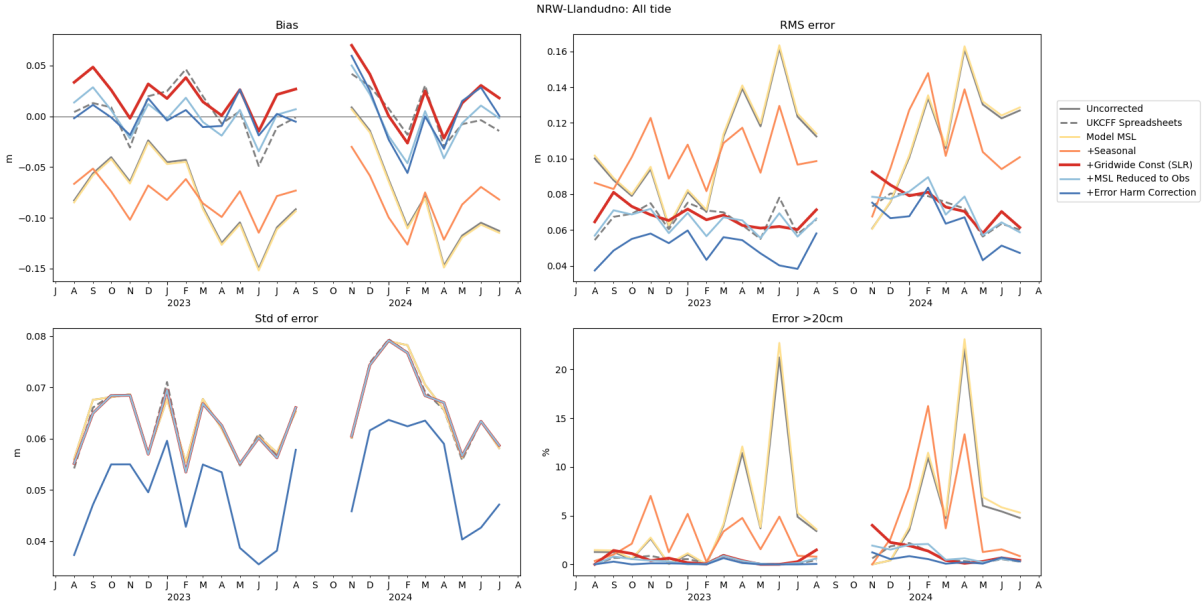

Figure A.49: All tide statistics for site NRW-Llandudno from August 2022–July 2024

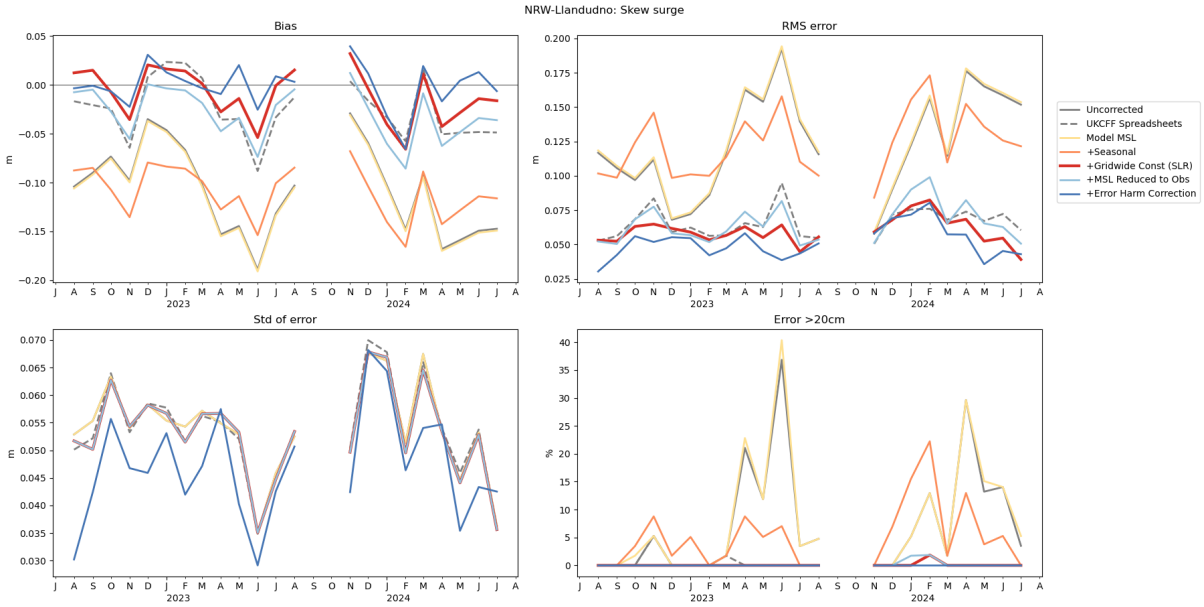

Figure A.50: Skew surge statistics for site NRW-Llandudno from August 2022–July 2024

© Crown Copyright 2025, Met Office

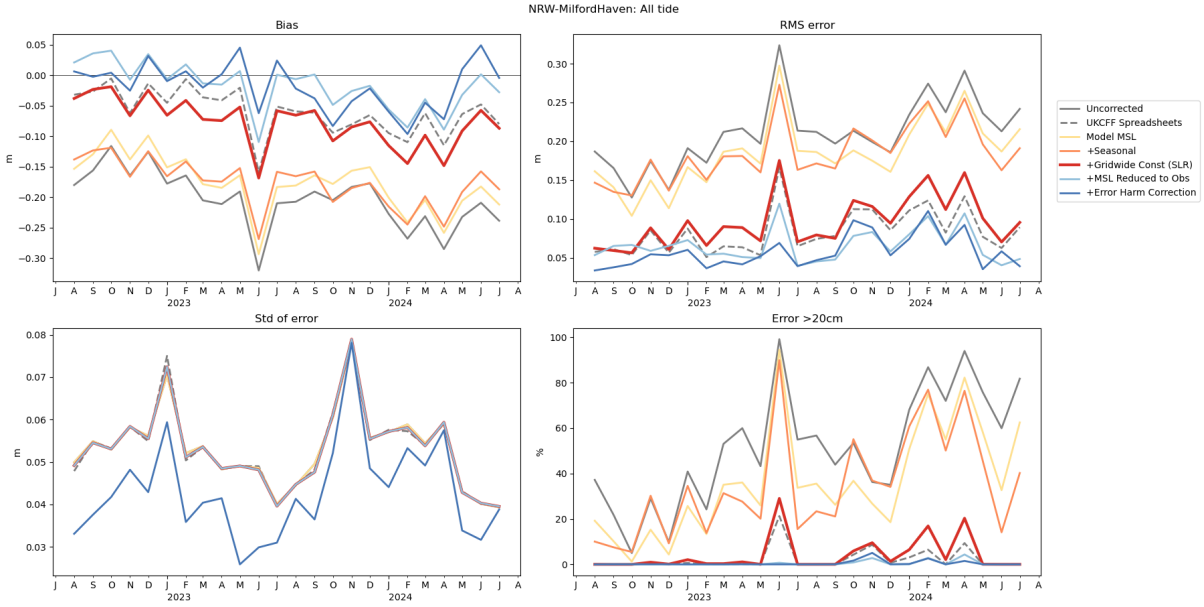

Figure A.51: All tide statistics for site NRW-MilfordHaven from August 2022–July 2024

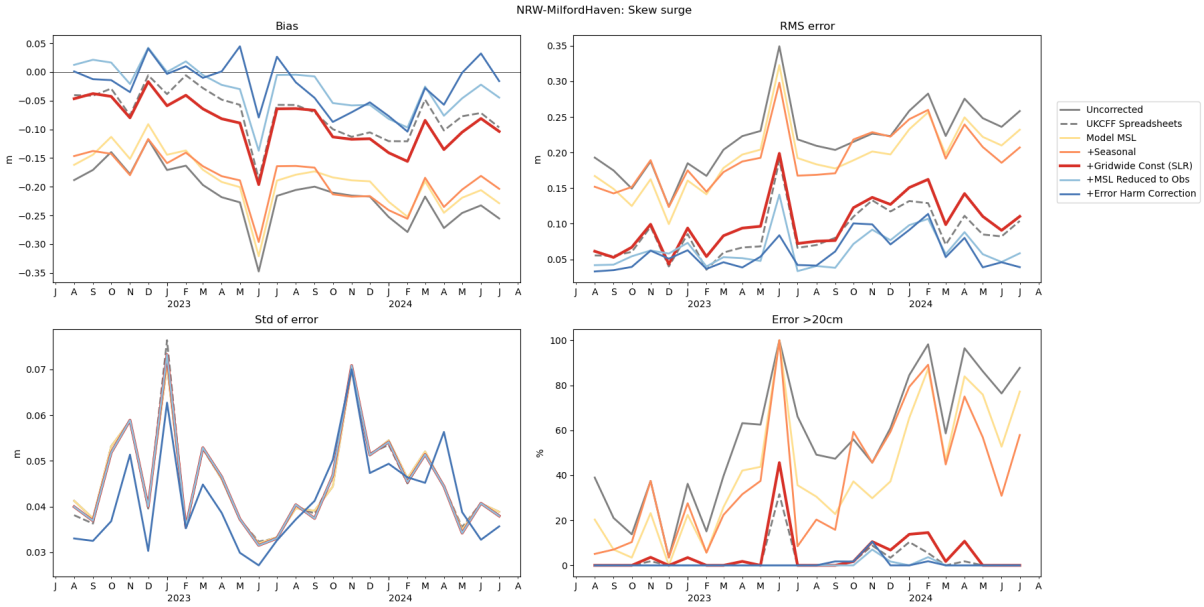

Figure A.52: Skew surge statistics for site NRW-MilfordHaven from August 2022–July 2024

© Crown Copyright 2025, Met Office

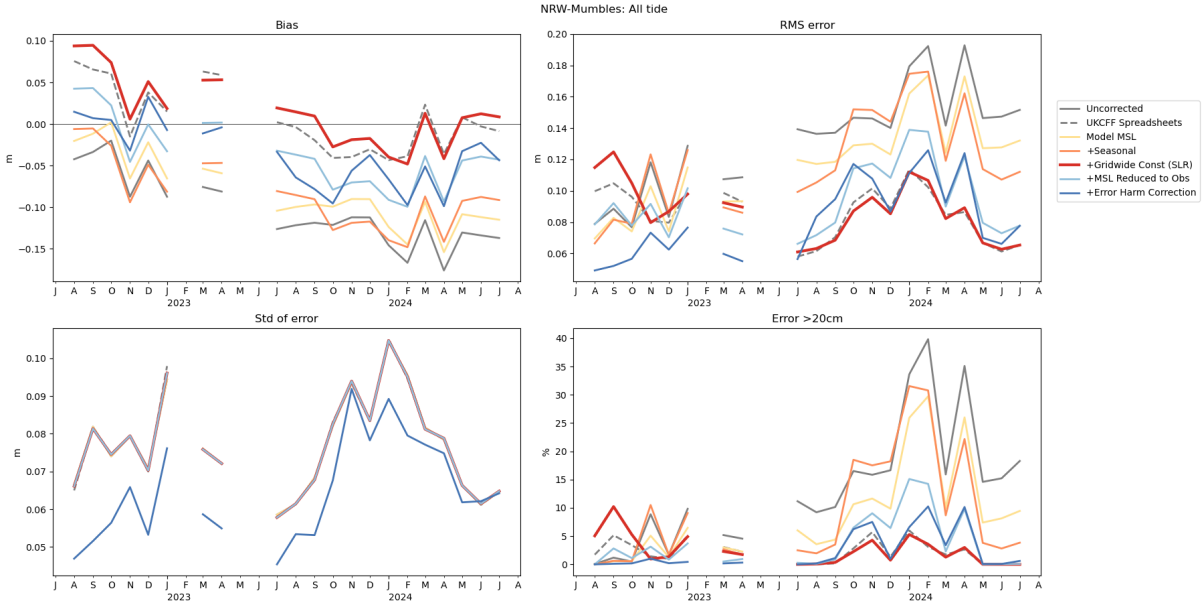

Figure A.53: All tide statistics for site NRW-Mumbles from August 2022–July 2024

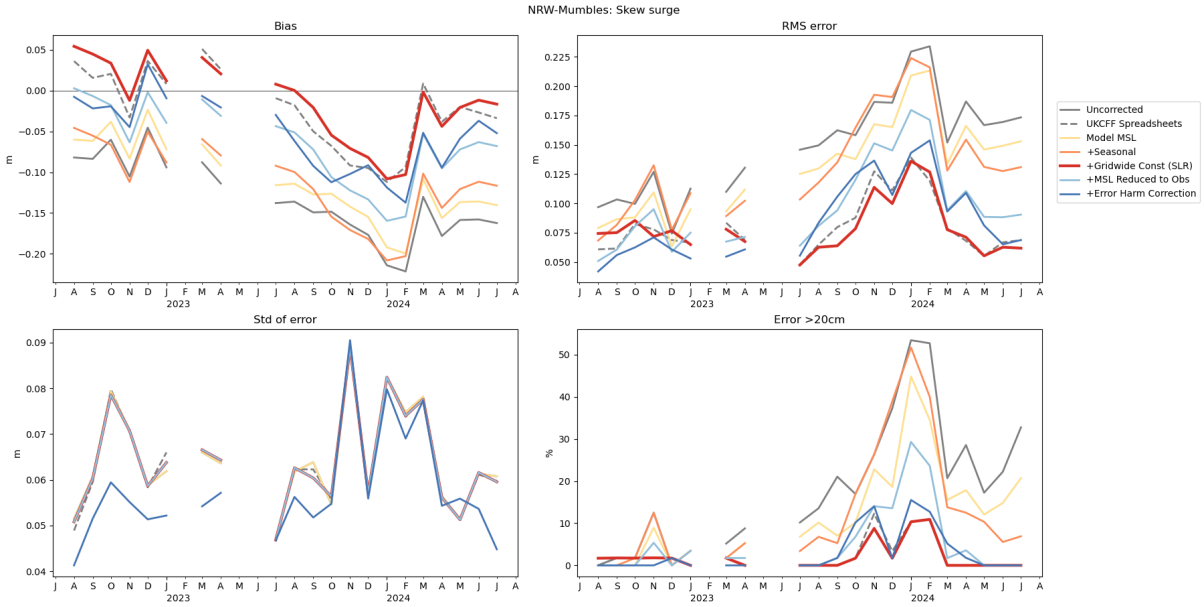

Figure A.54: Skew surge statistics for site NRW-Mumbles from August 2022–July 2024

© Crown Copyright 2025, Met Office

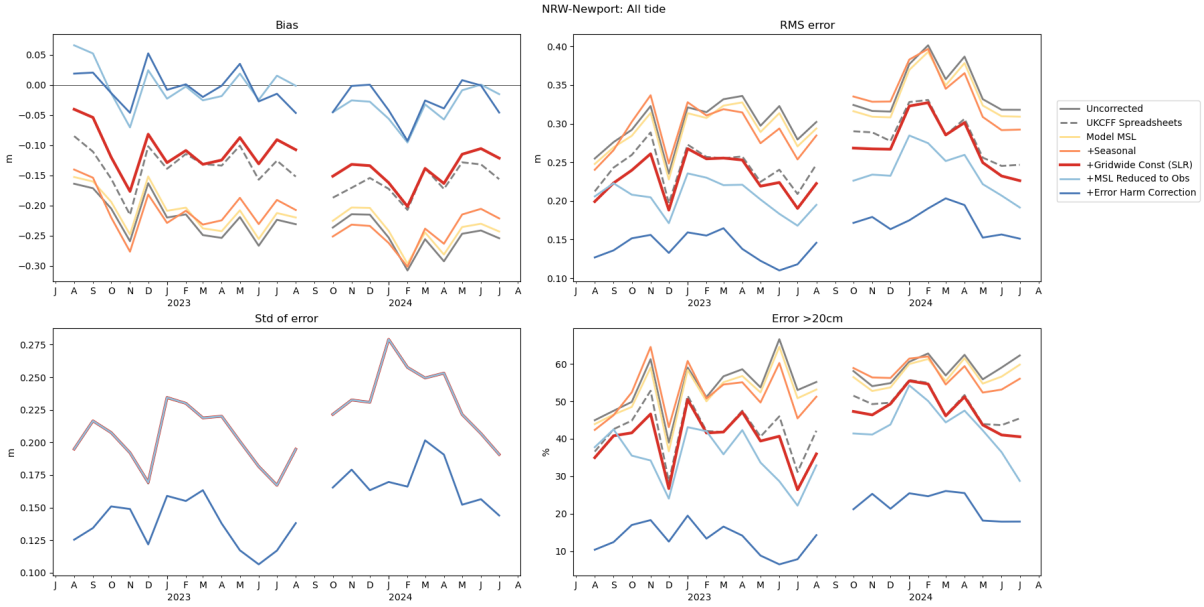

Figure A.55: All tide statistics for site NRW-Newport from August 2022–July 2024

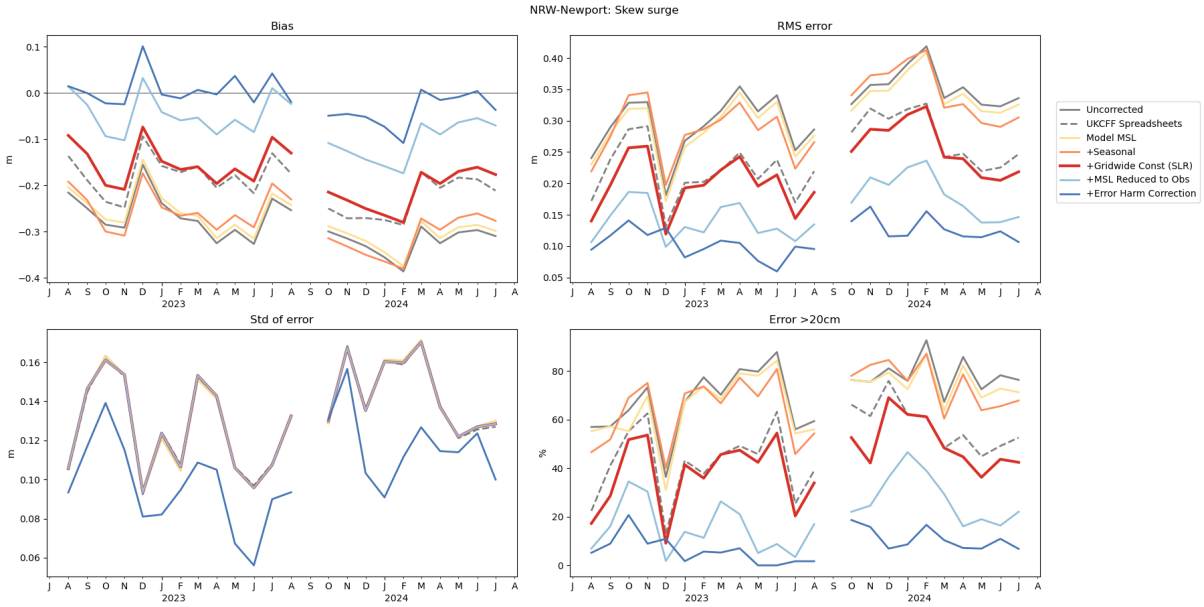

Figure A.56: Skew surge statistics for site NRW-Newport from August 2022–July 2024

© Crown Copyright 2025, Met Office

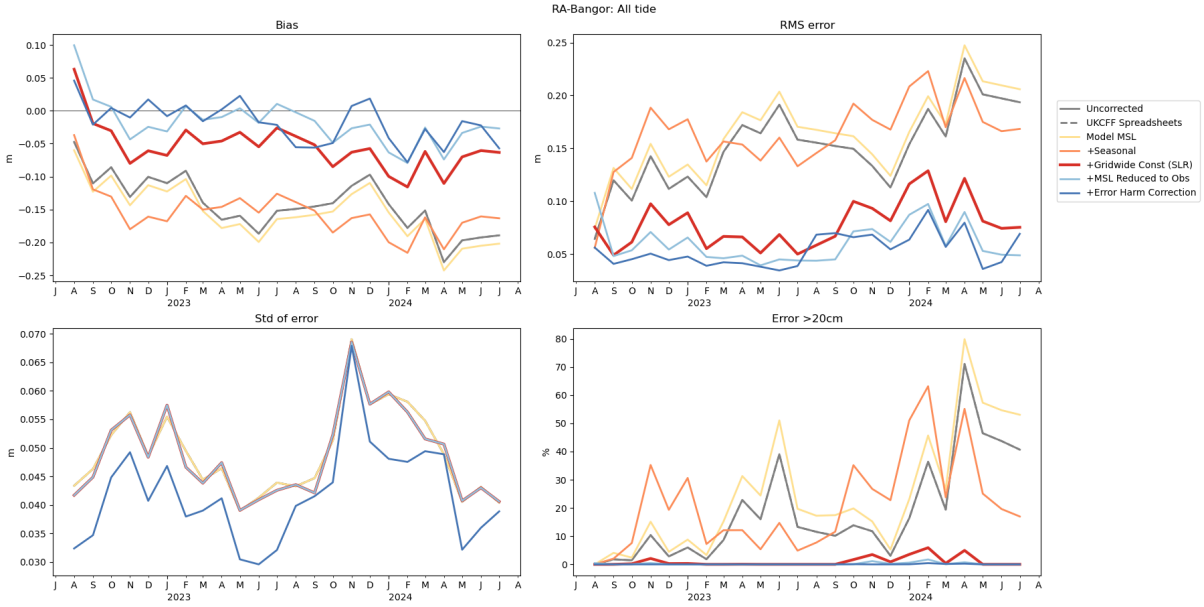

Figure A.57: All tide statistics for site RA-Bangor from August 2022–July 2024

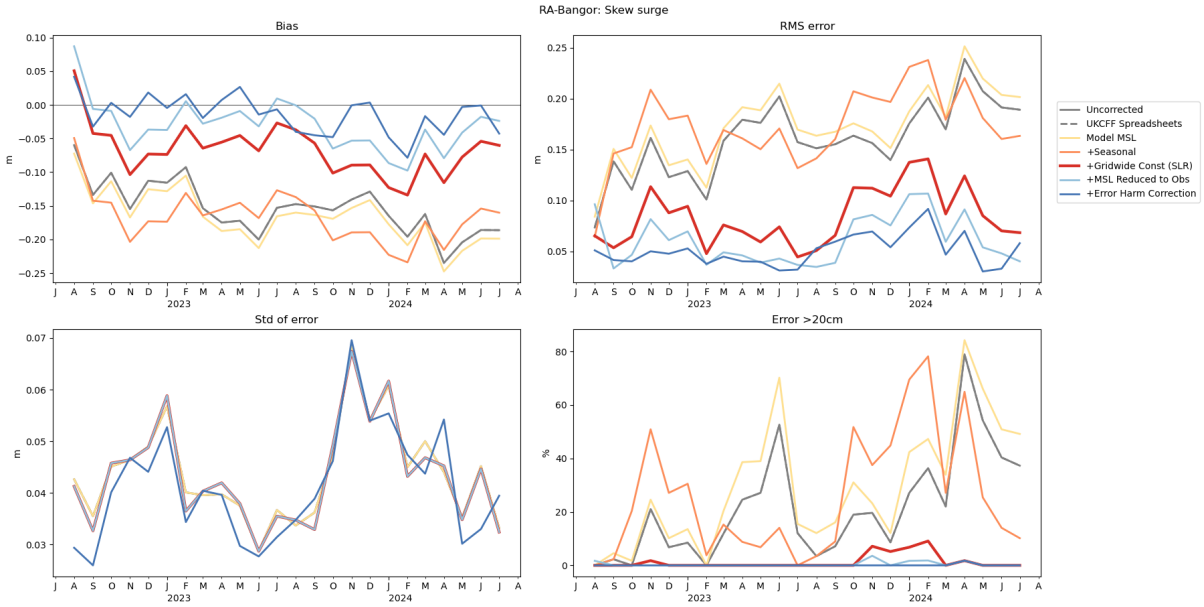

Figure A.58: Skew surge statistics for site RA-Bangor from August 2022–July 2024

© Crown Copyright 2025, Met Office

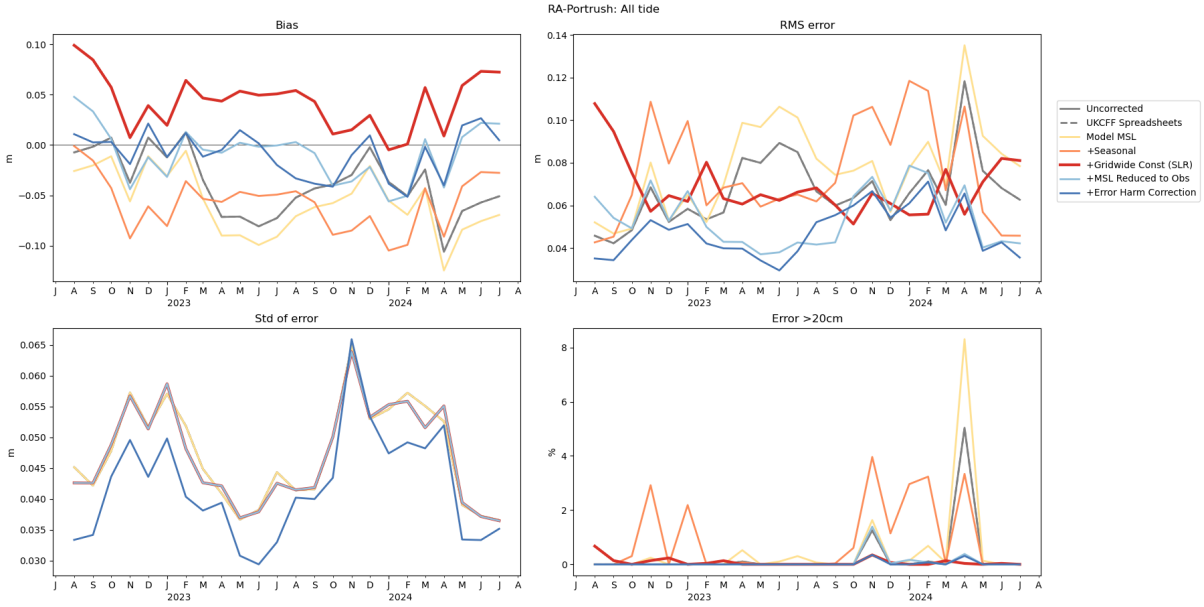

Figure A.59: All tide statistics for site RA-Portrush from August 2022–July 2024

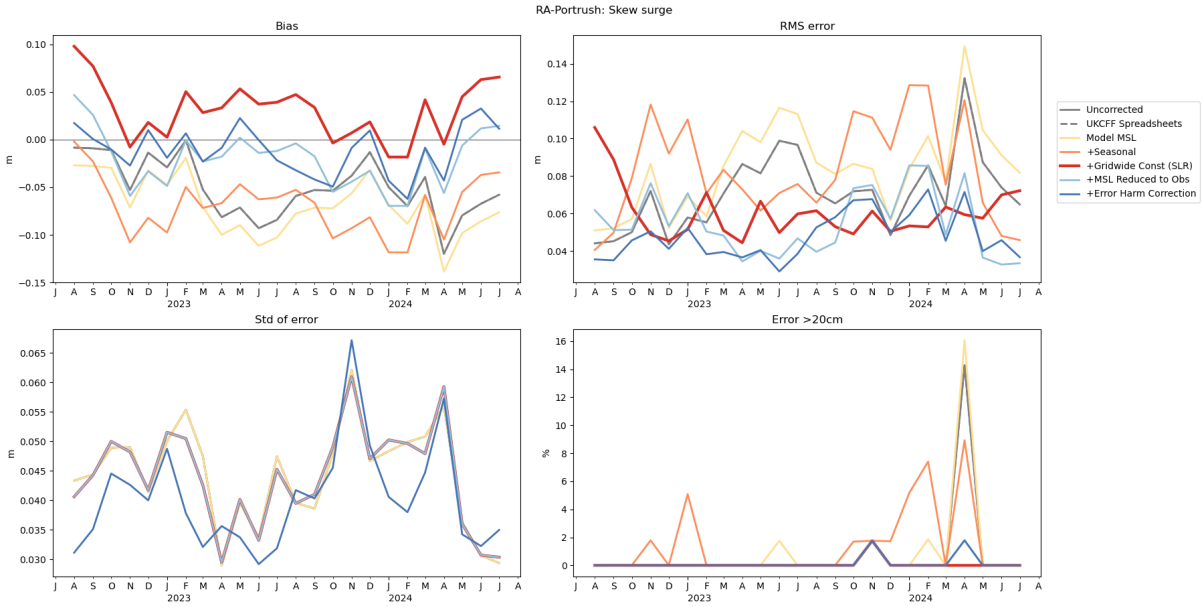

Figure A.60: Skew surge statistics for site RA-Portrush from August 2022–July 2024

© Crown Copyright 2025, Met Office

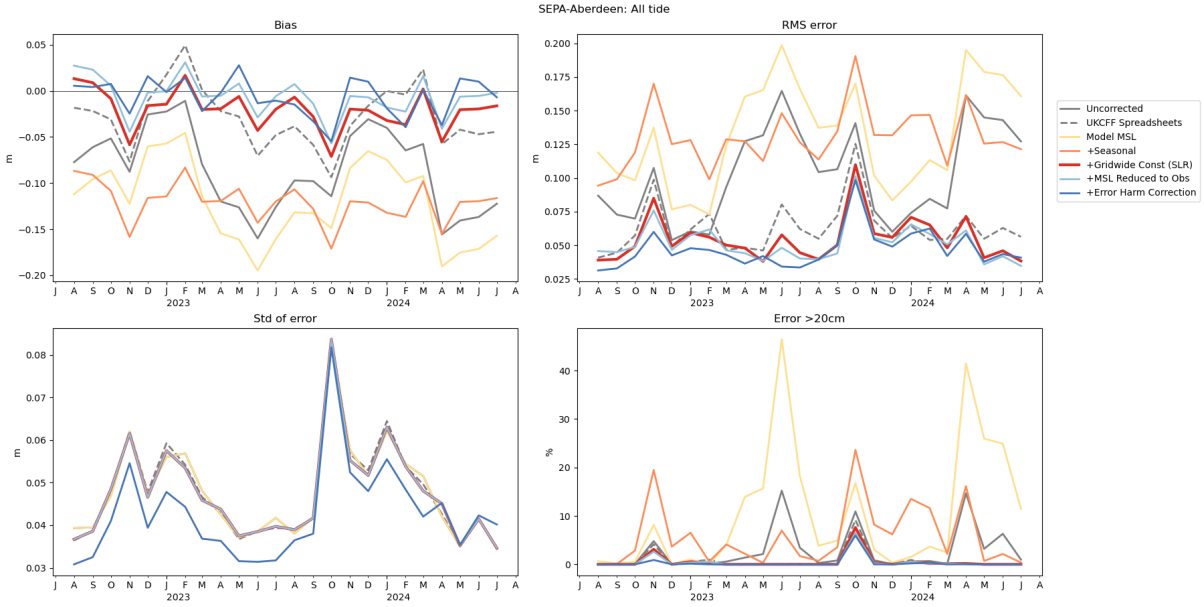

Figure A.61: All tide statistics for site SEPA-Aberdeen from August 2022–July 2024

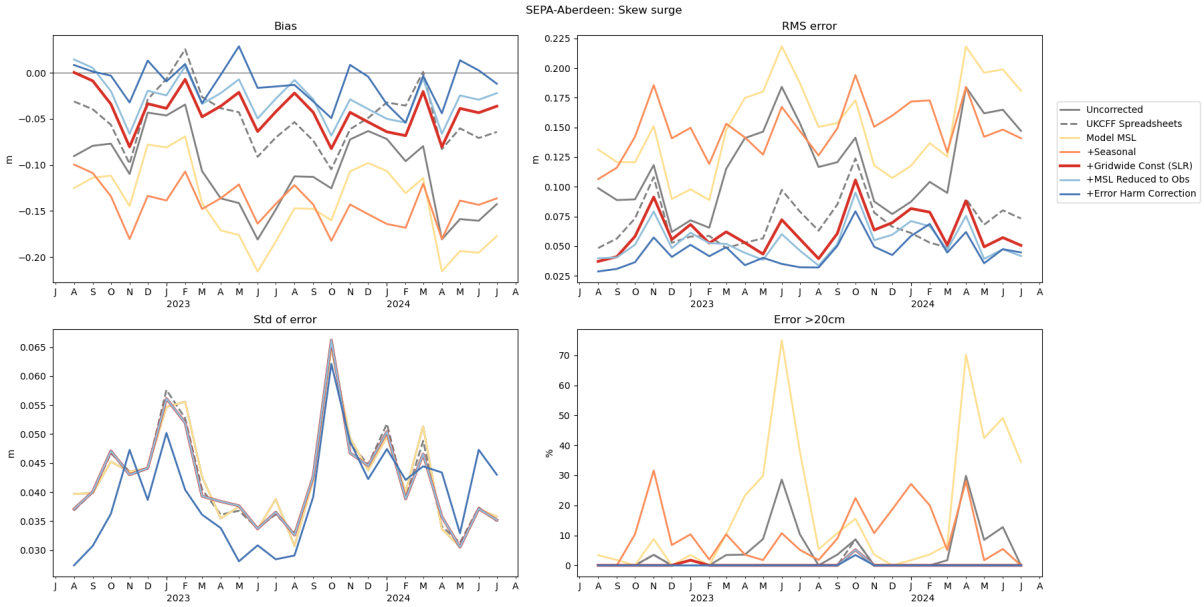

Figure A.62: Skew surge statistics for site SEPA-Aberdeen from August 2022–July 2024

© Crown Copyright 2025, Met Office

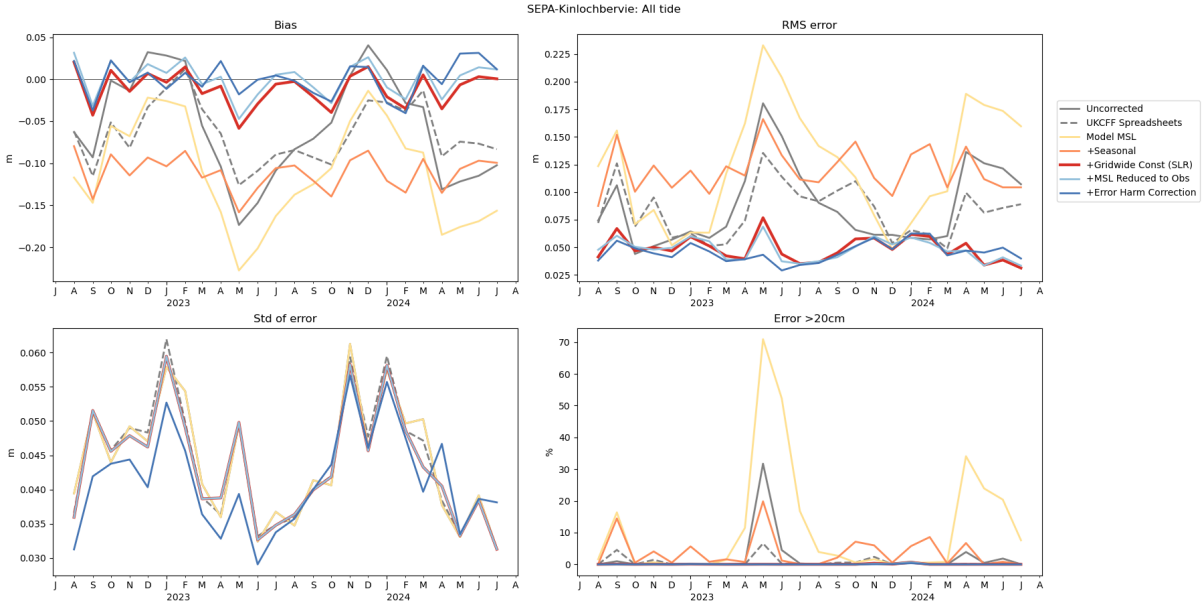

Figure A.63: All tide statistics for site SEPA-Kinlochbervie from August 2022–July 2024

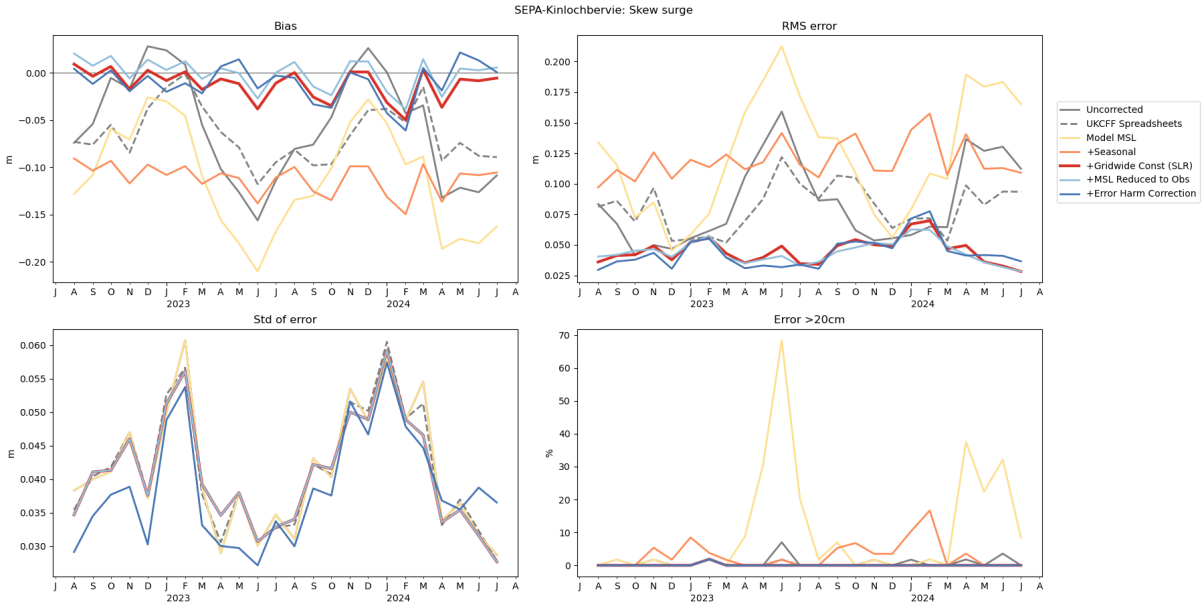

Figure A.64: Skew surge statistics for site SEPA-Kinlochbervie from August 2022–July 2024

© Crown Copyright 2025, Met Office

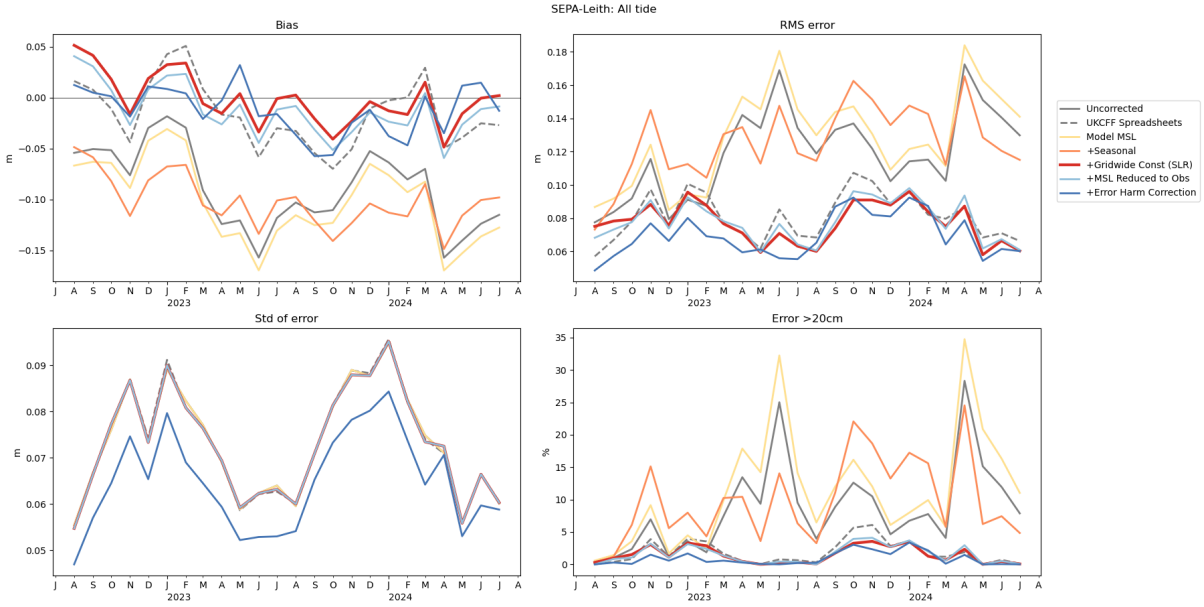

Figure A.65: All tide statistics for site SEPA-Leith from August 2022–July 2024

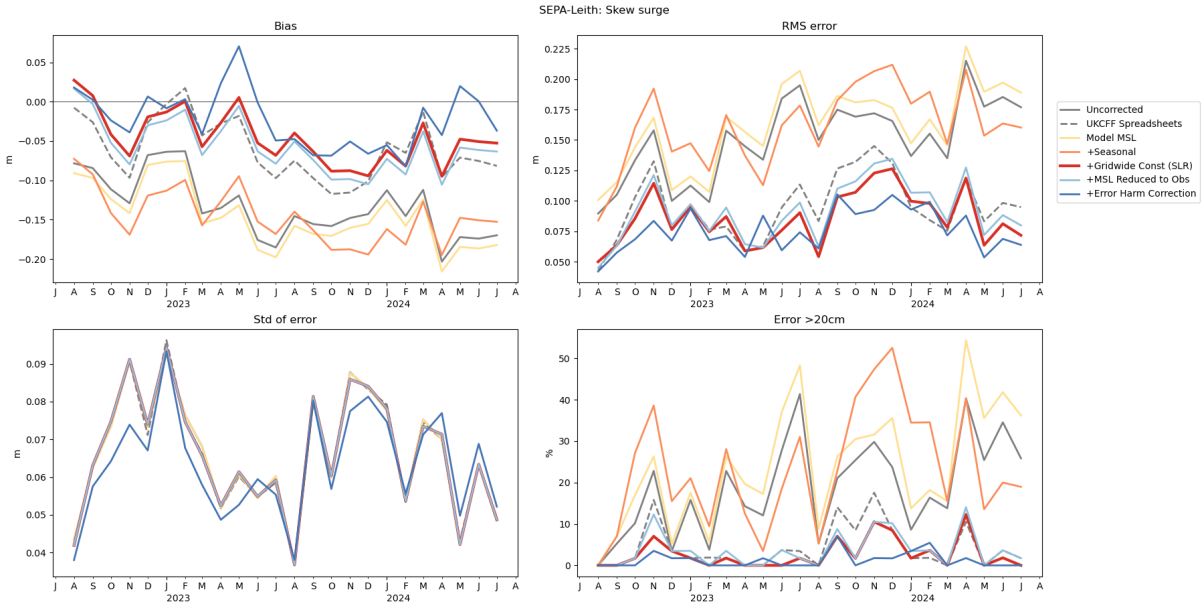

Figure A.66: Skew surge statistics for site SEPA-Leith from August 2022–July 2024

© Crown Copyright 2025, Met Office

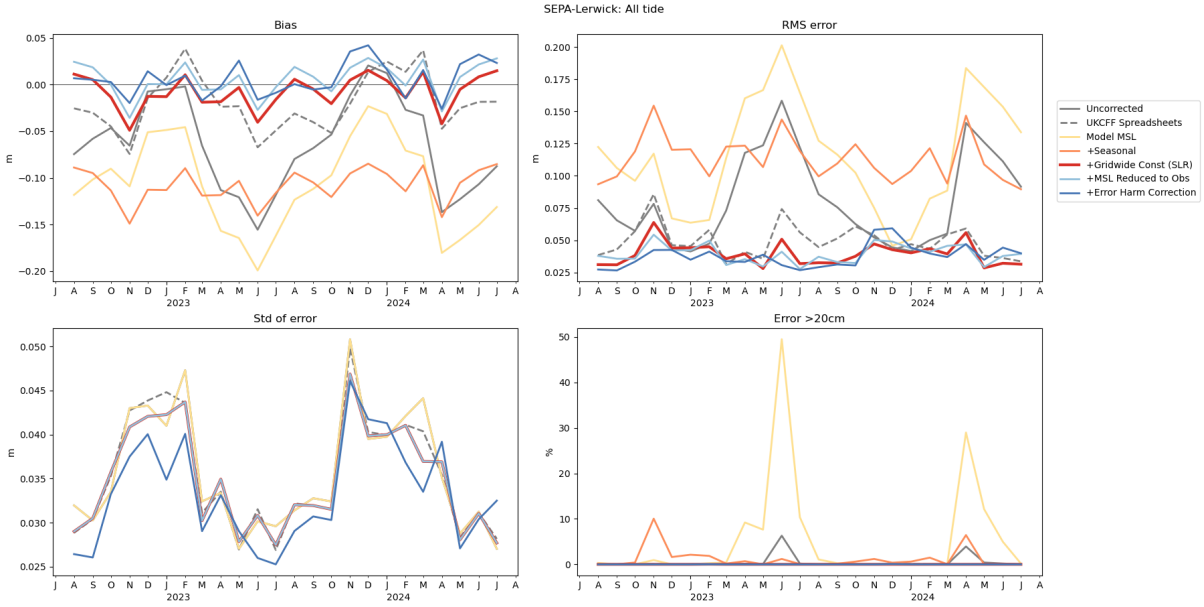

Figure A.67: All tide statistics for site SEPA-Lerwick from August 2022–July 2024

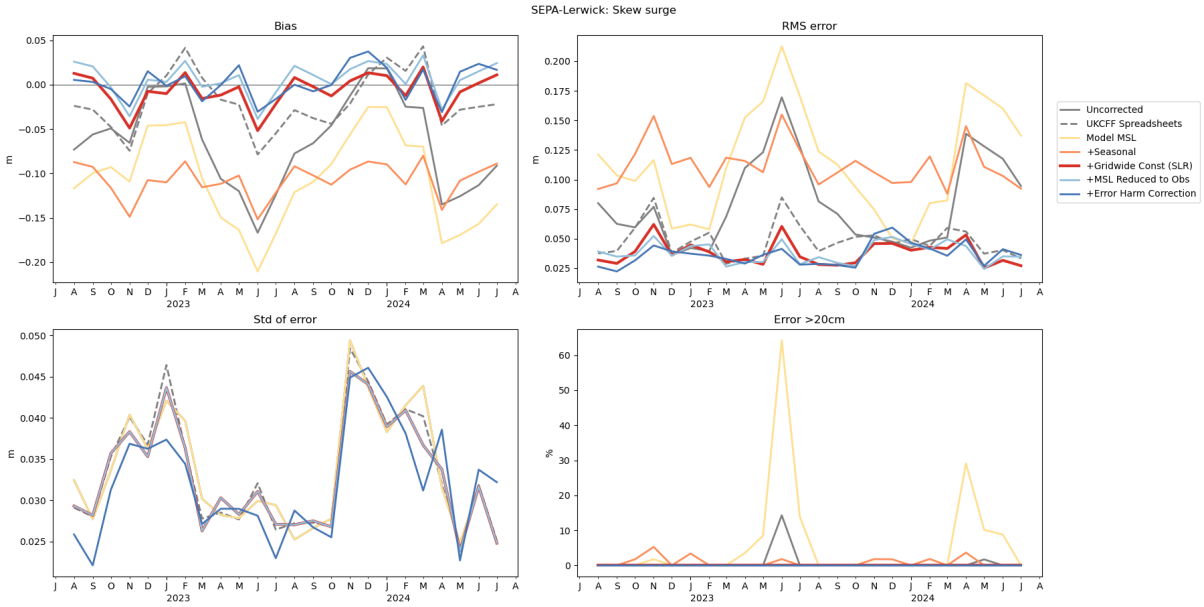

Figure A.68: Skew surge statistics for site SEPA-Lerwick from August 2022–July 2024

© Crown Copyright 2025, Met Office

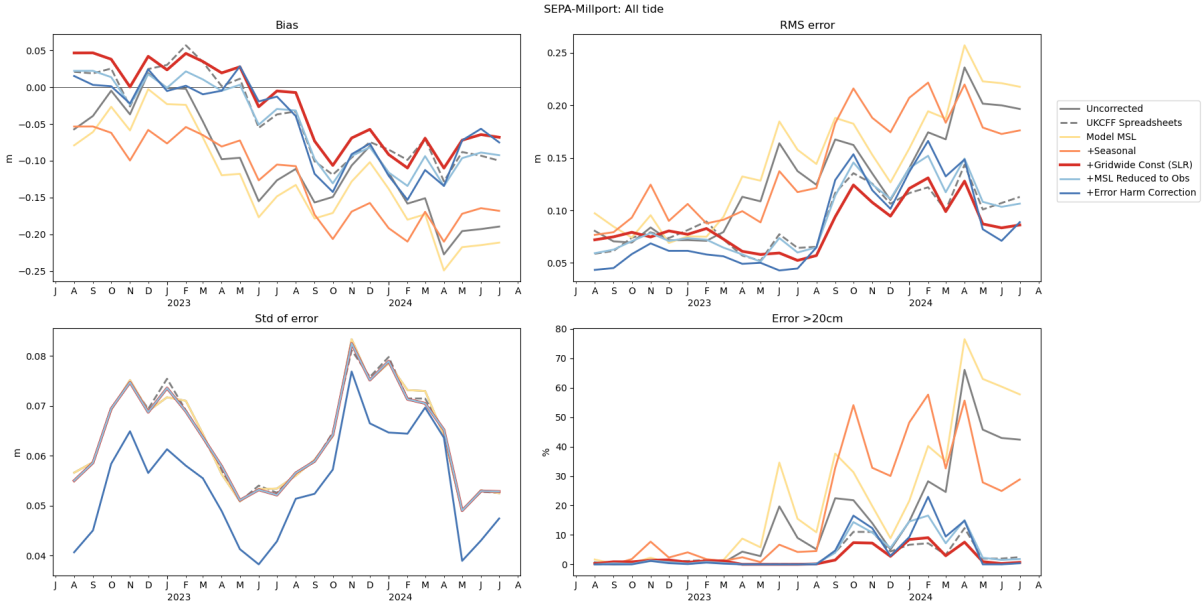

Figure A.69: All tide statistics for site SEPA-Millport from August 2022–July 2024

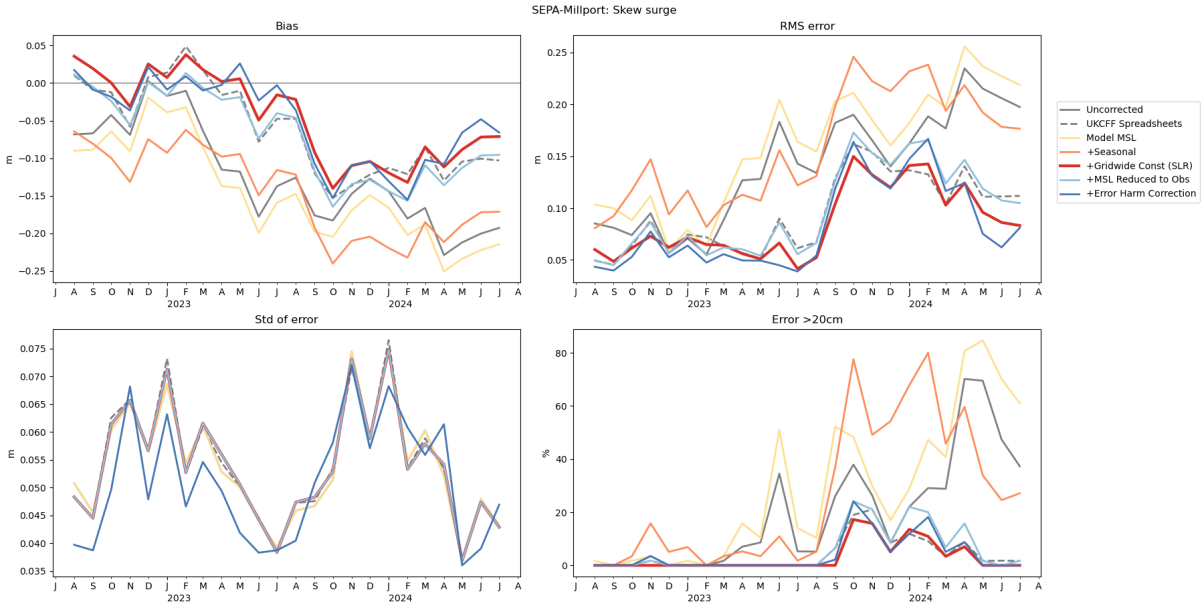

Figure A.70: Skew surge statistics for site SEPA-Millport from August 2022–July 2024

© Crown Copyright 2025, Met Office

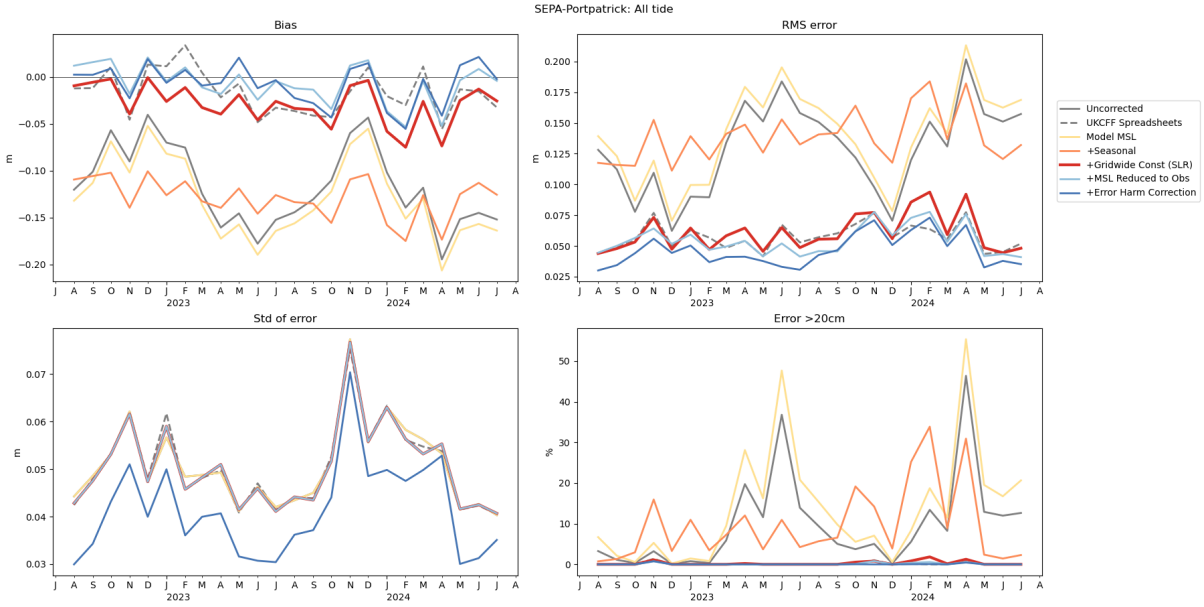

Figure A.71: All tide statistics for site SEPA-Portpatrick from August 2022–July 2024

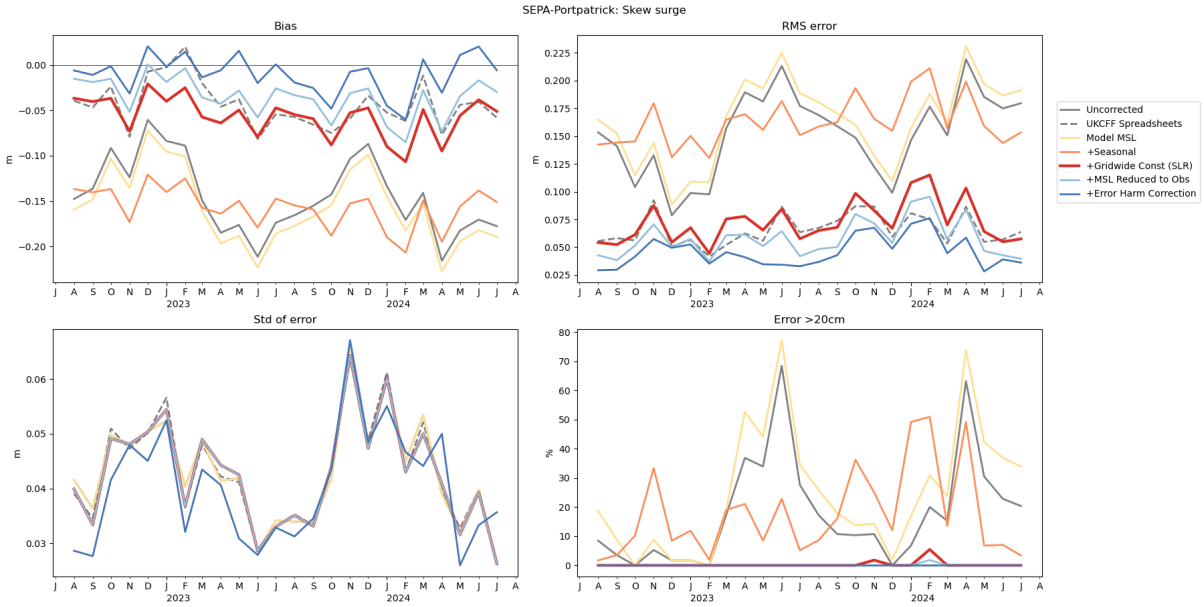

Figure A.72: Skew surge statistics for site SEPA-Portpatrick from August 2022–July 2024

© Crown Copyright 2025, Met Office

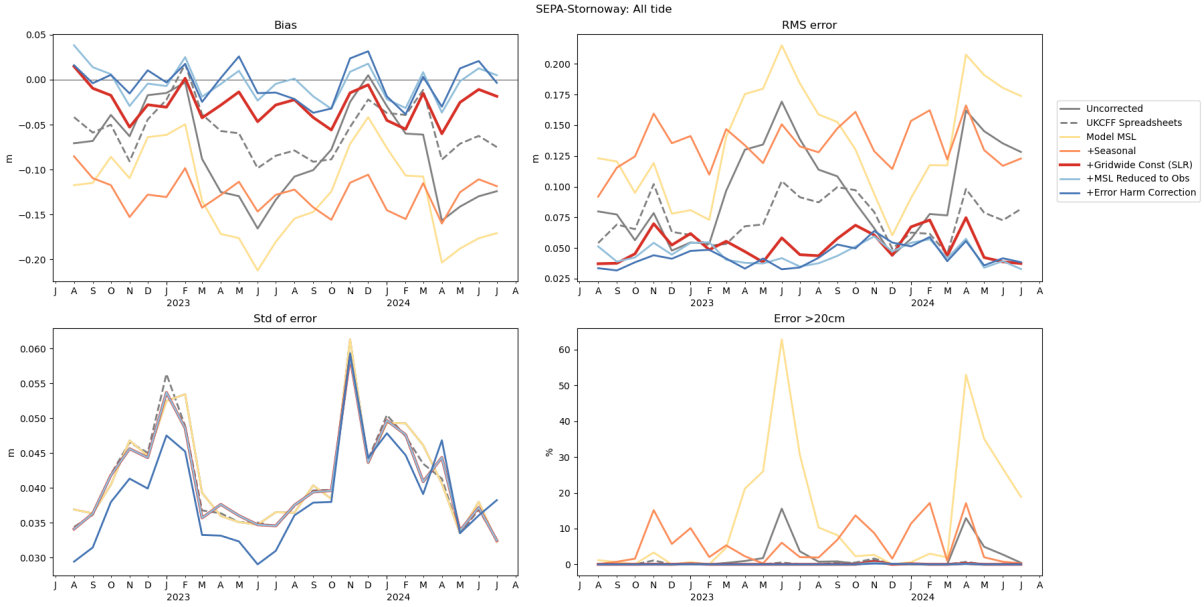

Figure A.73: All tide statistics for site SEPA-Stornoway from August 2022–July 2024

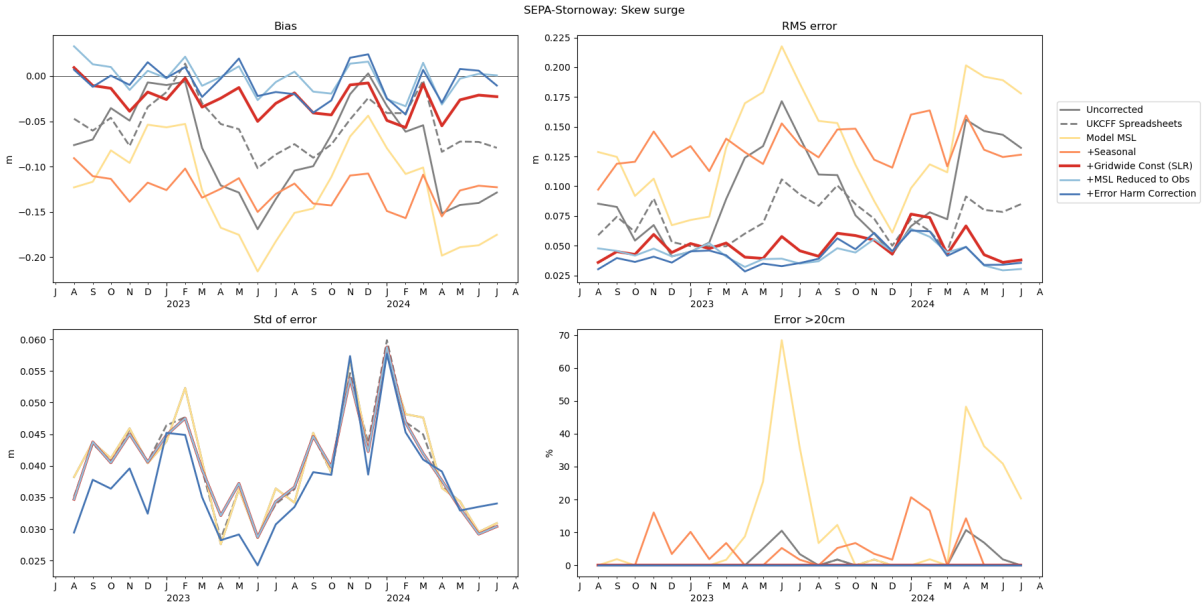

Figure A.74: Skew surge statistics for site SEPA-Stornoway from August 2022–July 2024

© Crown Copyright 2025, Met Office

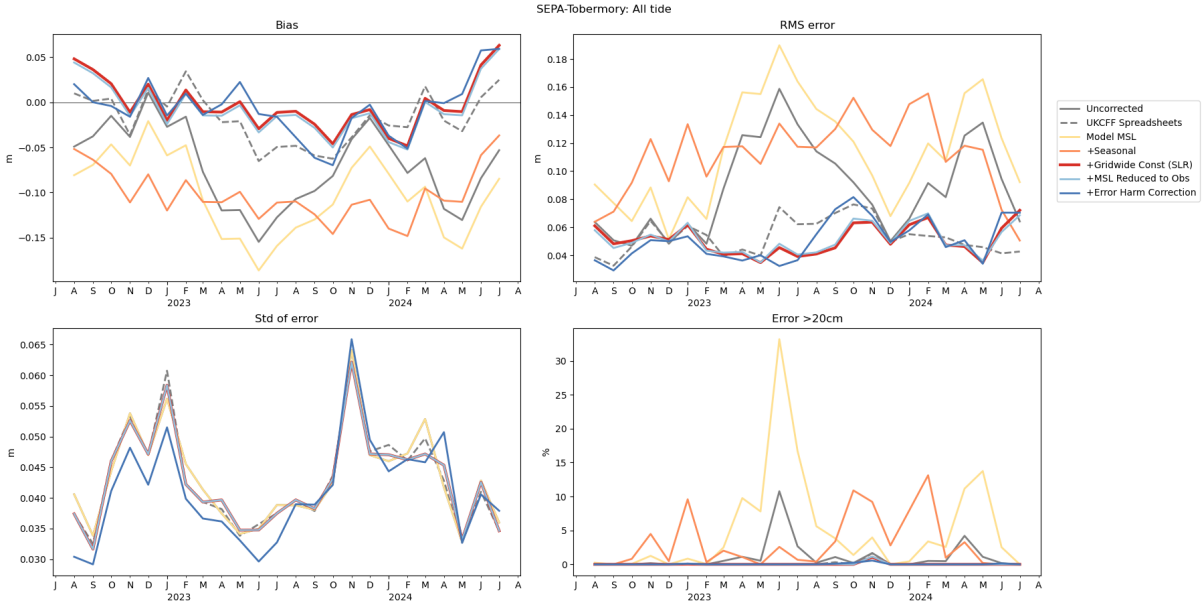

Figure A.75: All tide statistics for site SEPA-Tobermory from August 2022–July 2024

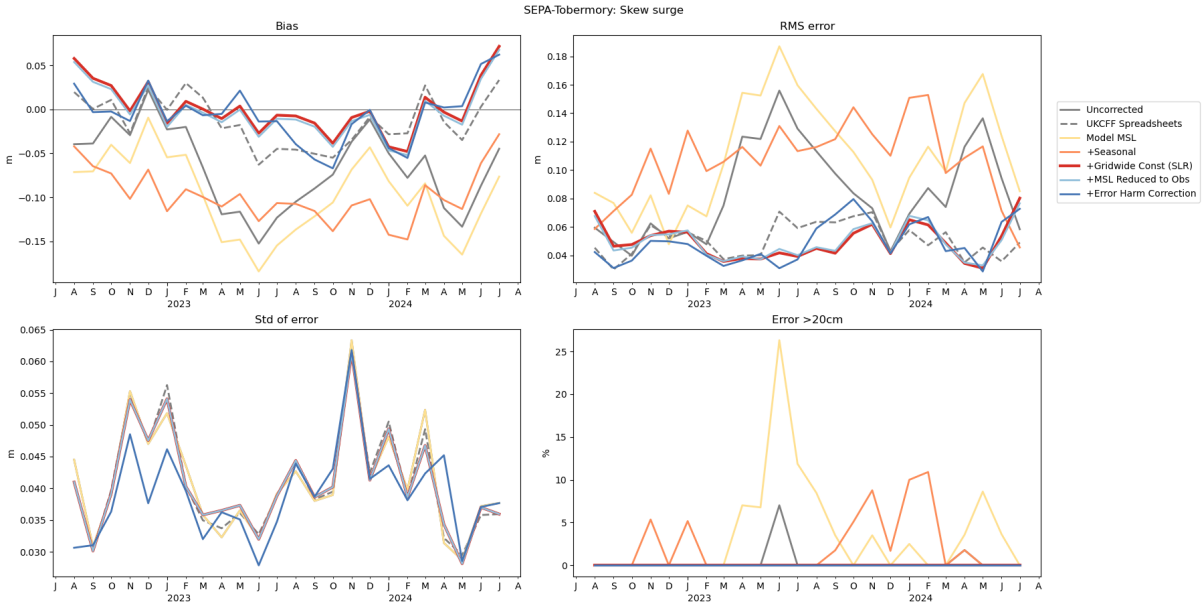

Figure A.76: Skew surge statistics for site SEPA-Tobermory from August 2022–July 2024

© Crown Copyright 2025, Met Office

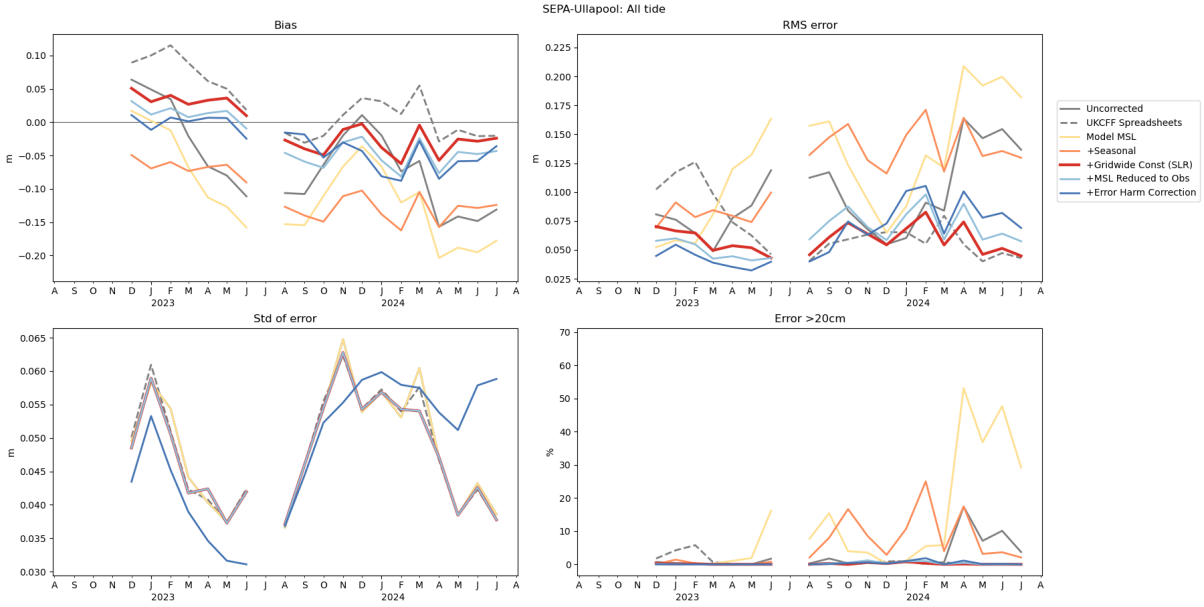

Figure A.77: All tide statistics for site SEPA-Ullapool from August 2022–July 2024

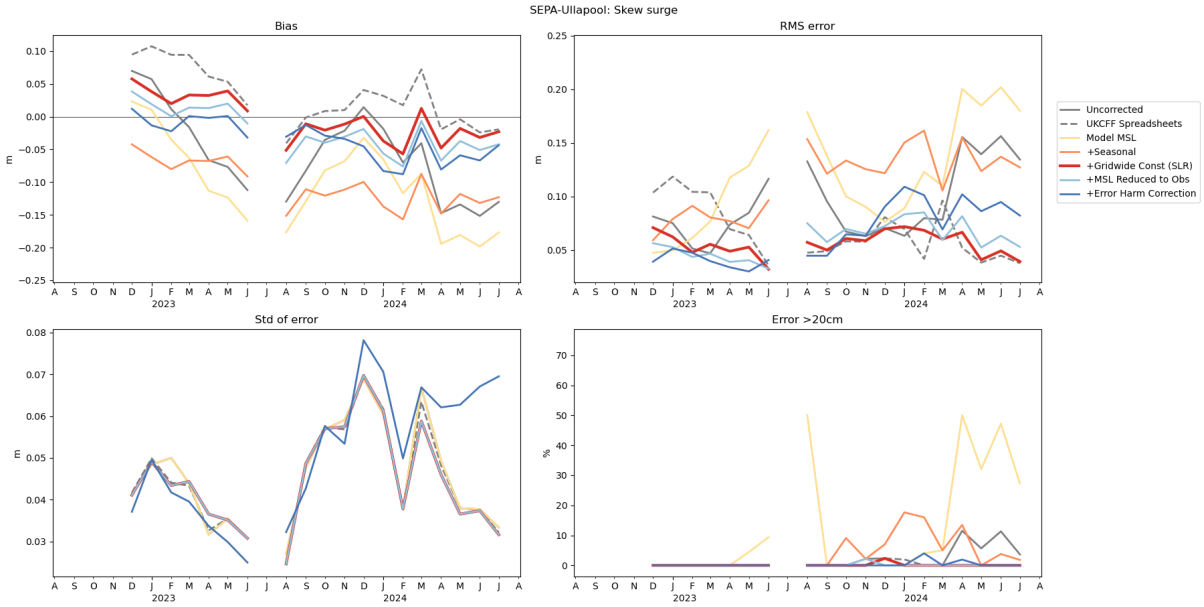

Figure A.78: Skew surge statistics for site SEPA-Ullapool from August 2022–July 2024

© Crown Copyright 2025, Met Office

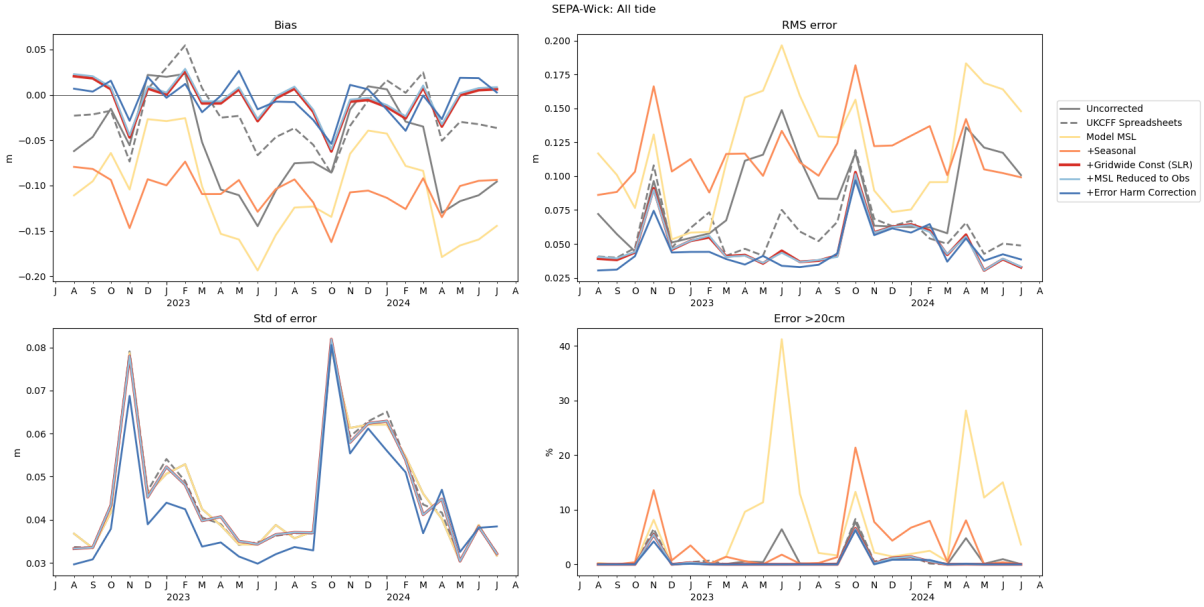

Figure A.79: All tide statistics for site SEPA-Wick from August 2022–July 2024

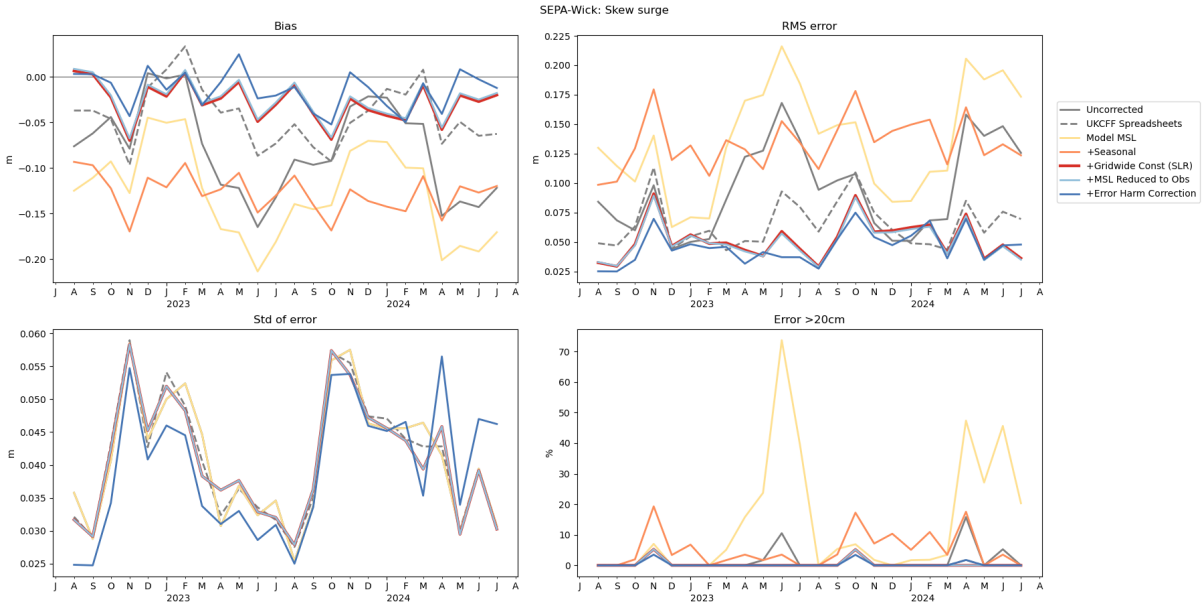

Figure A.80: Skew surge statistics for site SEPA-Wick from August 2022–July 2024

© Crown Copyright 2025, Met Office

Met Office
FitzRoy Road
Exeter
Devon
EX1 3PB
United Kingdom

Produced with the Met Office LaTeX template v3.0.0